# Closure Representations on the .NET CLR

## Experiments and Observations

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# A real problem…

- .NET language-level interop is largely solved:
  - e.g. objects, calling conventions, exceptions
  - e.g. C# can easily call VB
  - e.g. SML can easily catch C# exceptions
  - e.g. SML.NET can understand C# classes
- BUT:
  - Scheme: Untyped function values
  - Standard ML: Typed function values
  - Haskell: Typed function values, also delayed computations
  - OCaml: Typed function values
  - Funnel: Typed function values, also delayed computations
  - Mercury: Typed function values
  - …

# A real problem…

- No interop over ANY of these constructs
  - A function value from one language cannot easily be used in another language
  - There are subtle and not-so-subtle differences between them.
  - Even if there isn't, compilers all encode them in different ways.
- The question: Can we do anything about this?

# Overview

- Definitions and Aims
- A Range of Possible Standardized Encodings
- Experimental Results
- Conclusions & Ways Forward

# Source Languages

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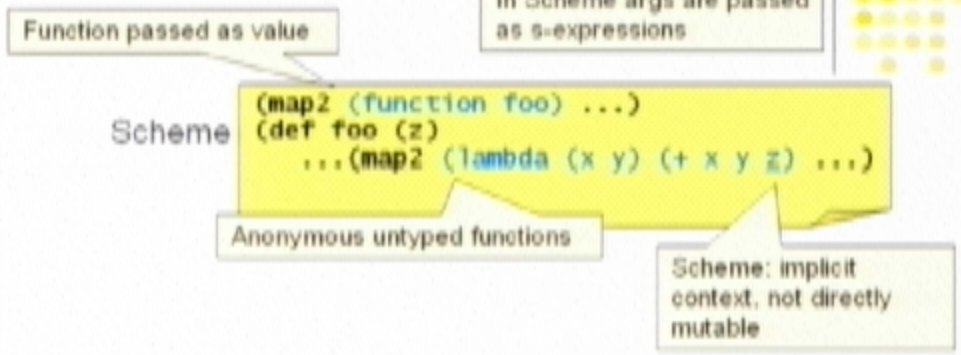
Scheme

```
(map2 (function foo) ...)
(def foo (z)
   ...(map2 (lambda (x y) (+ x y z) ...)
```

# Source Languages



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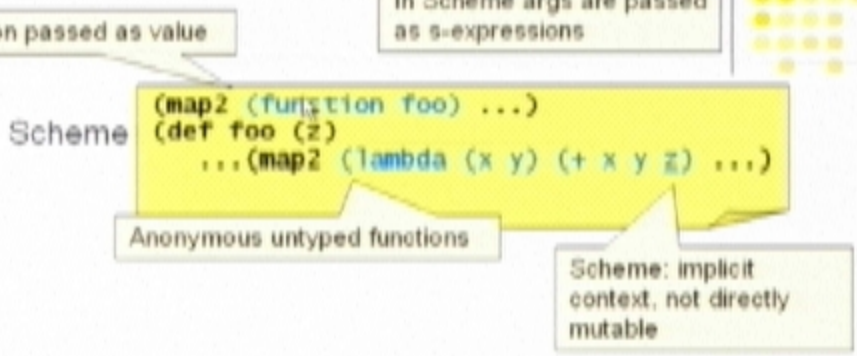

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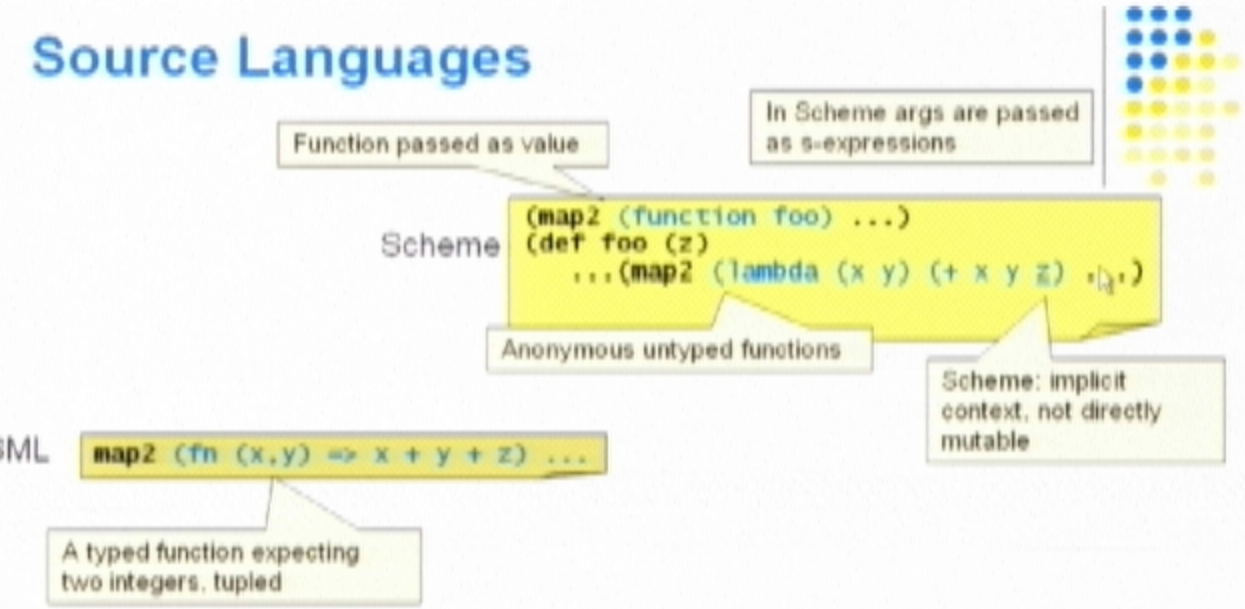

# Source Languages

Function passed as value

In Scheme args are passed as s-expressions

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Anonymous untyped functions

Scheme: implicit context, not directly mutable

ML

```
map2 (fn (x,y) => x + y + z) ...
```

A typed function expecting two integers, tupled

Again typed

OCaml

```
map2 (fun x y -> x + y + z) ...
=== map2 (fun x -> (fun y -> x + y + z)) ...
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Functions return functions ("currying") are very common

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=== map2 (fun x -> (fun y -> x + y + z)) ...
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Functions return functions ("currying") are very common

Haskell

```
map2 (\x y. f x + f y + f z) ...
```

Again typed, again lots of currying, also lots of delayed computations

# Definitions

- Closures: "functions in a context"
  - Context = Environment = Free Variables
- Closure expressions: declarations that specify new inner functions and their contexts (context is usually implicit)
- Function value: "code pointer + data" = an object allocated to hold pointer(s) to the function code plus the environment
- Function application: invoking a function value
- Function type: a general class of types that function values belong to.

# Aims

- Fully-specified encoding of closures into MS-IL
- Easy to generate
- Supports separate compilation (no global analysis needed).
- Fast enough for, e.g. OCaml
- Fits with MS-IL polymorphism/generics

# Example

GC#

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let rename = 0;

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   if (v = valOld) then
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Functional language

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This closure expression uses elements from the environment. Each time we call "map" a new function object will be allocated.

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When invoked the function object calls this function. It can have side-effects.

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This is an encoded generic function type

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Assume all closure expressions are named with the environment annotated.

# Part 2: Implementation Choices

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# Part 2: Implementation Choices

# Overview

- Note: for typed functional languages we really assume Generics have been added to the CLR

Generics == Parametric Polymorphism == Templates

# Choices & Non-choices

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Encoding function types as generic MS-IL types seems obvious: structural equivalence comes for free.

Note: could also build these into MS-IL. e.g. make delegates structural.

Note: System.Func could still be a class, value class, interface or a general class of delegates

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The relevant parts of the environment must be somehow accessed via fields of the function object

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Choice: How do we get from the function value to the code? i.e. how is the code is "stored" in/accessed from function object.

Getting from A to B is an indirect call. On the .NET CLR, class vtables, interface vtables, delegates or code pointers are the only choices.


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# The Simplest Implementation

- Encoding into virtual methods

```
abstract class System.Func<A,B> {
    virtual B apply(A);
}

class clo : System.Func<string,string> {
   private string valOld;
   private string valNew;
   override string apply(string) { ... }
}

   .. new clo(...) ...
   .. f.apply() ...
```

- Code = virtual method
- Environment: stored inline in object

# The Simplest Implementation

- Encoding into virtual methods

This is the space of function types.

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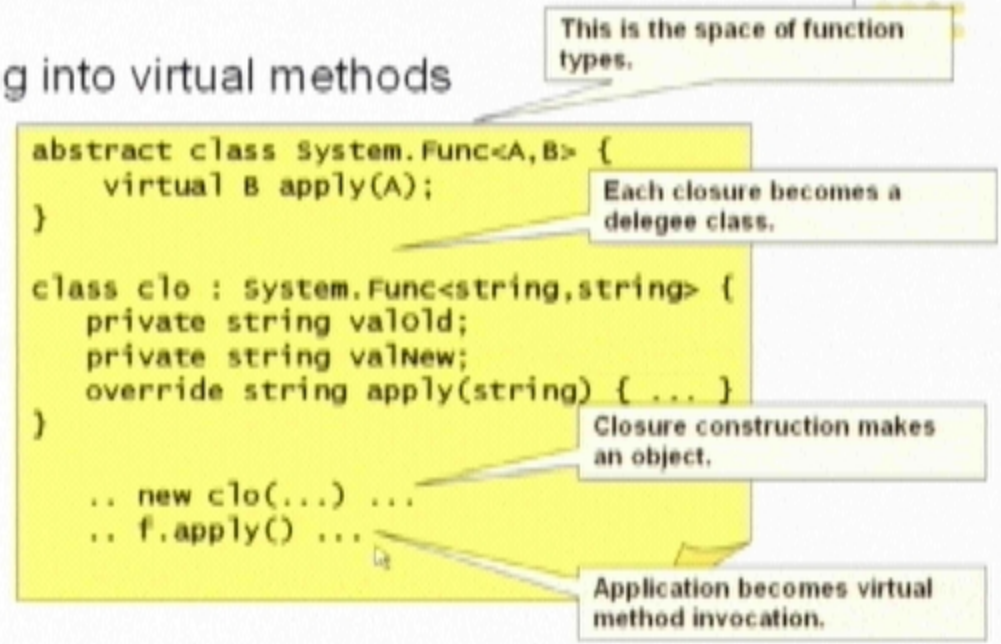


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delegate B System.Func<A,B>(A);

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Closure construction makes a delegee and a delegate.

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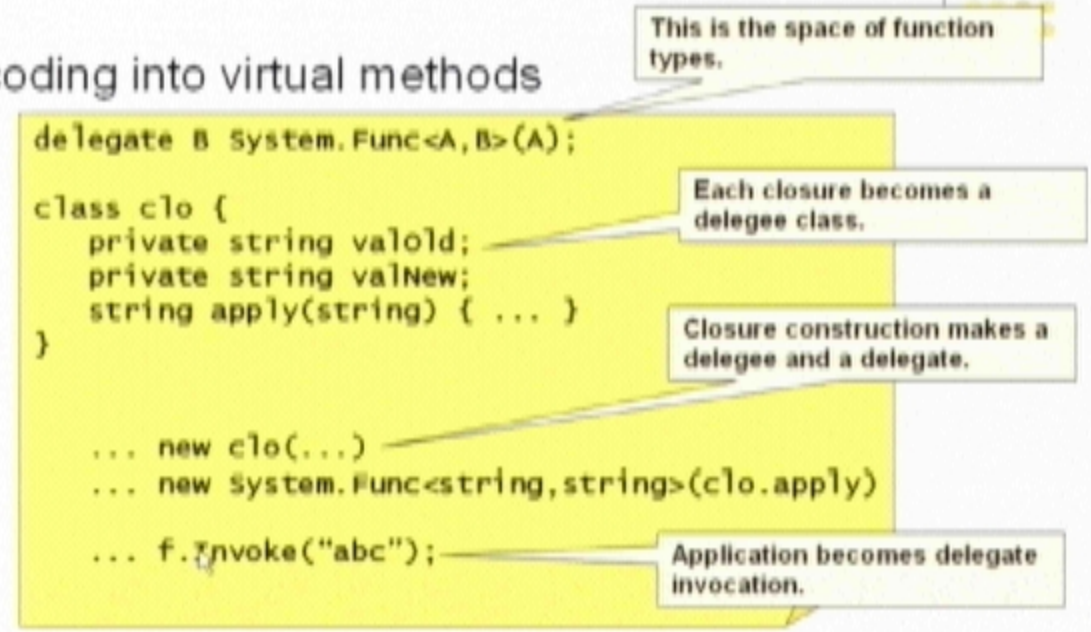


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# A Library Implementation

- Encode into:
  - MS-IL C-style function pointers;
  - Closure "template" classes

```
abstract class System.Func<A,B> {
   void * code;
}

static method B app<A,B>(System.Func<A,B>, A x)
{ ... }

class System.Clo<E,A,B> : System.Func<A,B> {
   Clo(E env, method B *(E env,A x) code);
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This is a helper method for application.

This class is a template for all closures.

This is the environment.

This is a "C-function pointer type" in MS-IL

Client code is verifiable, but the implementation of this module can use unsafe tricks if needed. Presume the library is code-signed.

# Part 3: Further Details of Implementation Choices

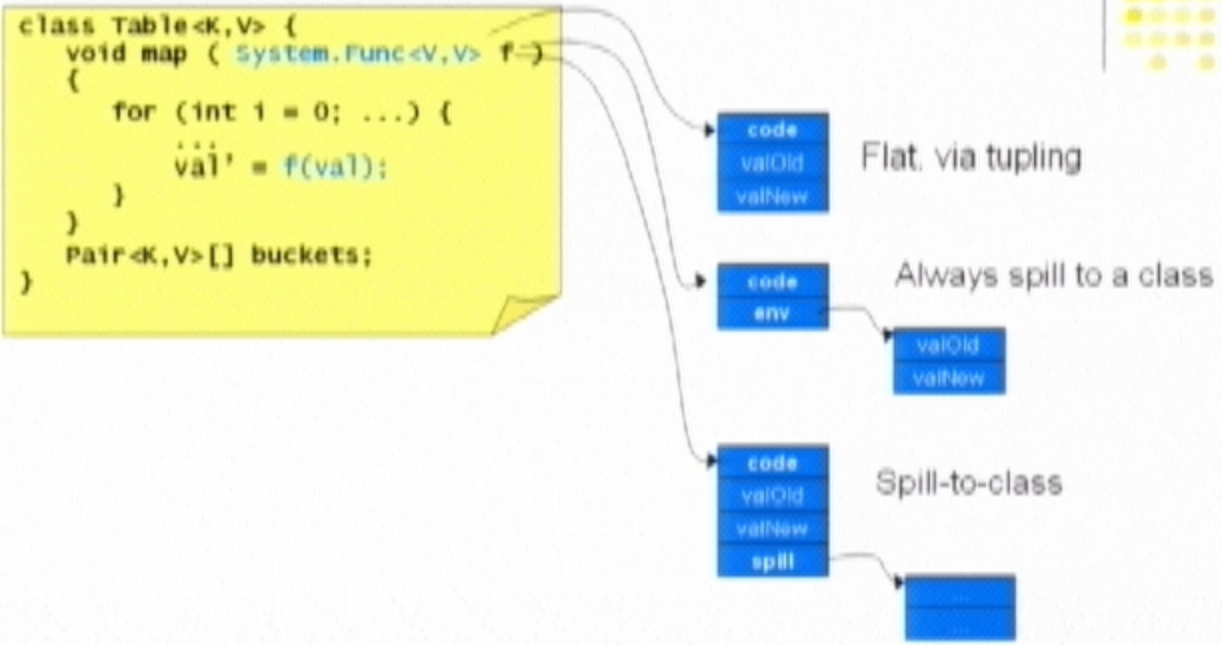
# Choices: Environments

```
class Table<K,V> {
   void map ( System.Func<V,V> f )
   {
      for (int i = 0; ...) {
         ...
         val' = f(val);
      }
   }
   Pair<K,V>[] buckets;
}
```


Flat, via tupling

Always split to a class?

# Choices: Environments



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}
```

For closure templates, a flat effect can be achieved by using "tupling", e.g. instantiating "E" with, e.g. Pair<int,int> or Tuple4<int,int,int,int>


Flat, via tupling


Always spill to a class



Spill-to-class

In our tests this is a new class per closure when needed

# Choices: Code

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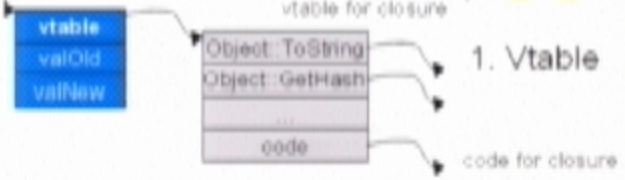

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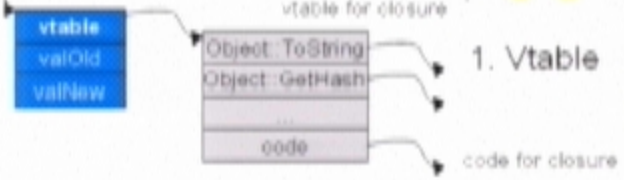

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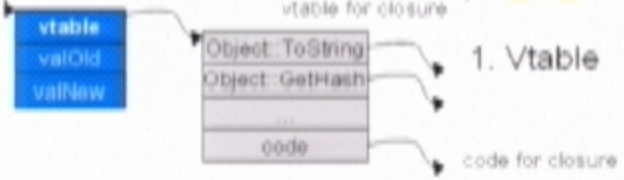

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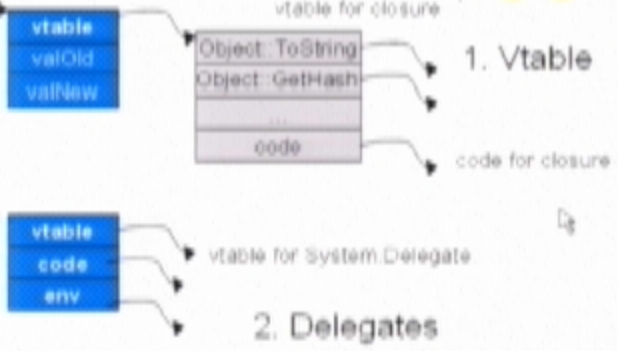

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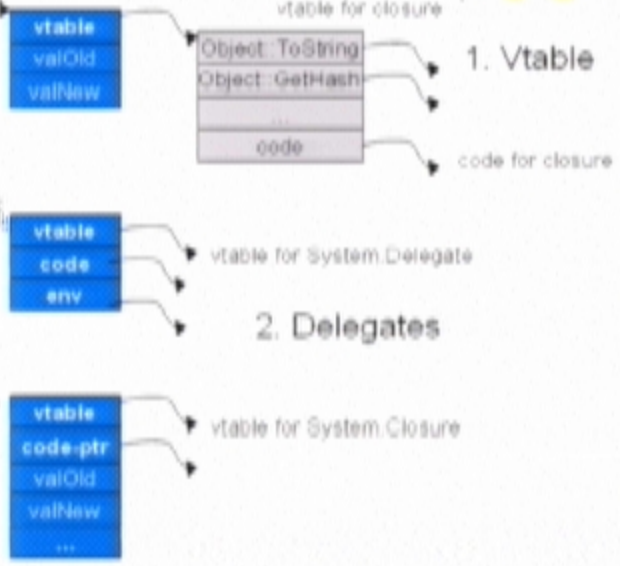

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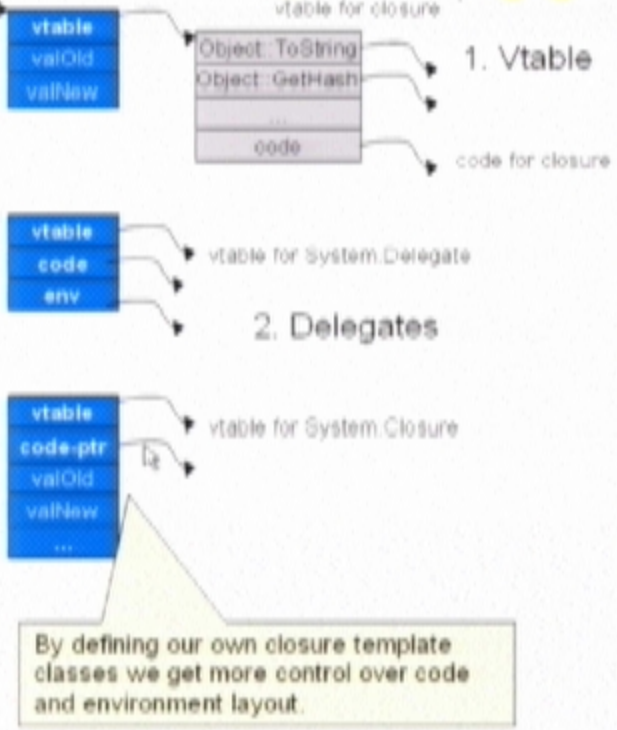

# Choices: Multiple Entries

Scheme

```
(map2 (lambda (x y) (+ x y z)) ...

(def map2 (f l1 l2) ...
      (f (car l1) (car l2)) ...
```

```
(def add2 (f x l2) ...
      (f x 4) ...
```

# Choices: Multiple Entries

Optimized functional language implementations play multiple entry point games.

Scheme

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(map2 (lambda (x y) (+ x y z)) ...

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This call passes 2 objects to a function expecting 2 objects. No need to allocate arguments as a S-expr!

Solution: extra entry point on closures for passing 2 objects

This call will then go much faster.

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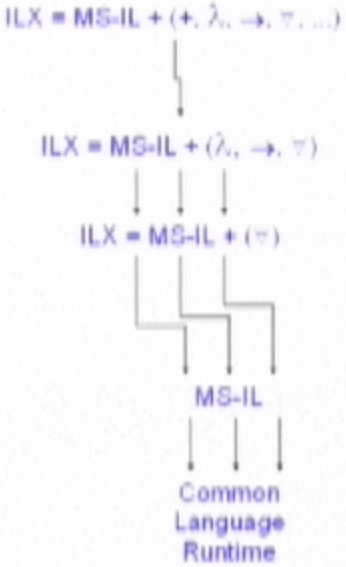
# Part 4: Experimental Results

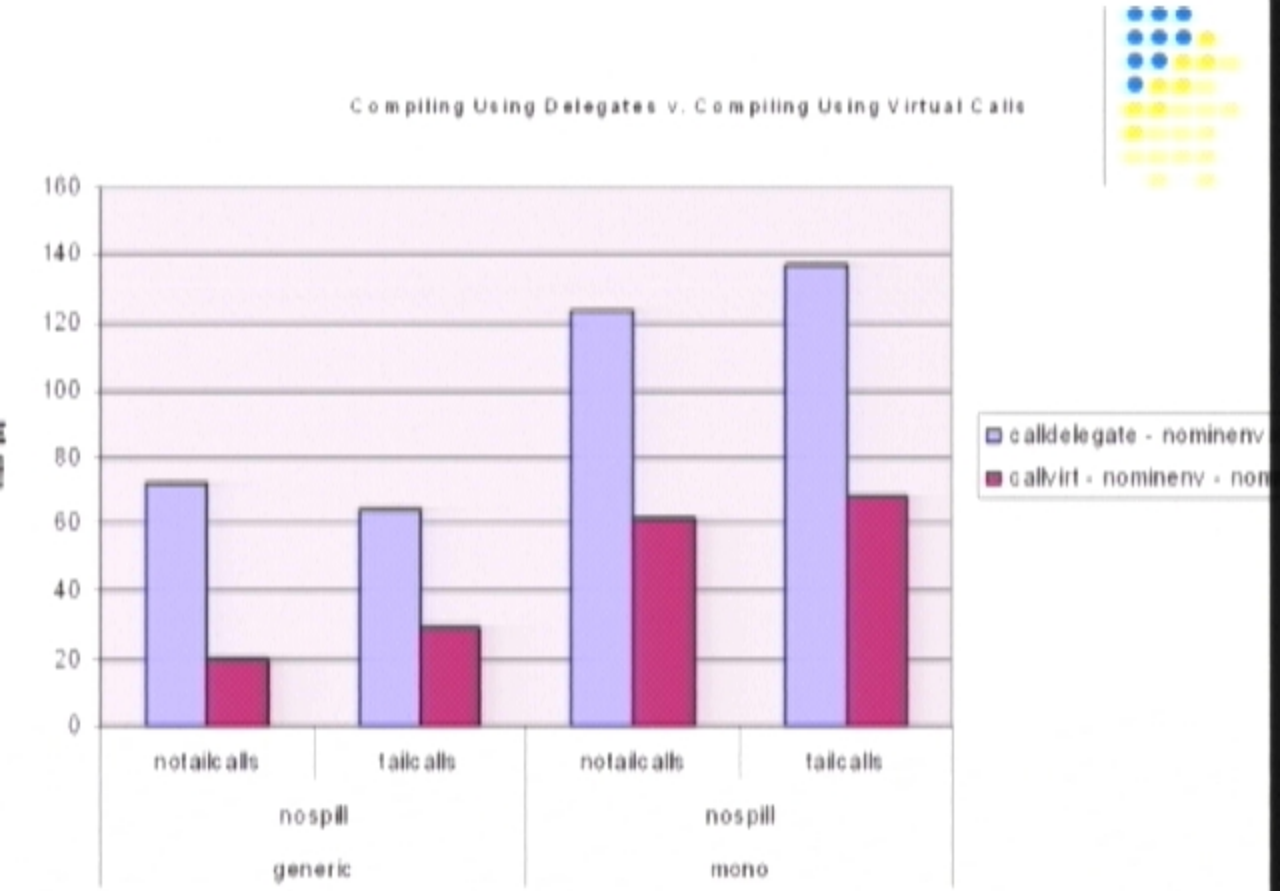
# ILX Implementations by Translation

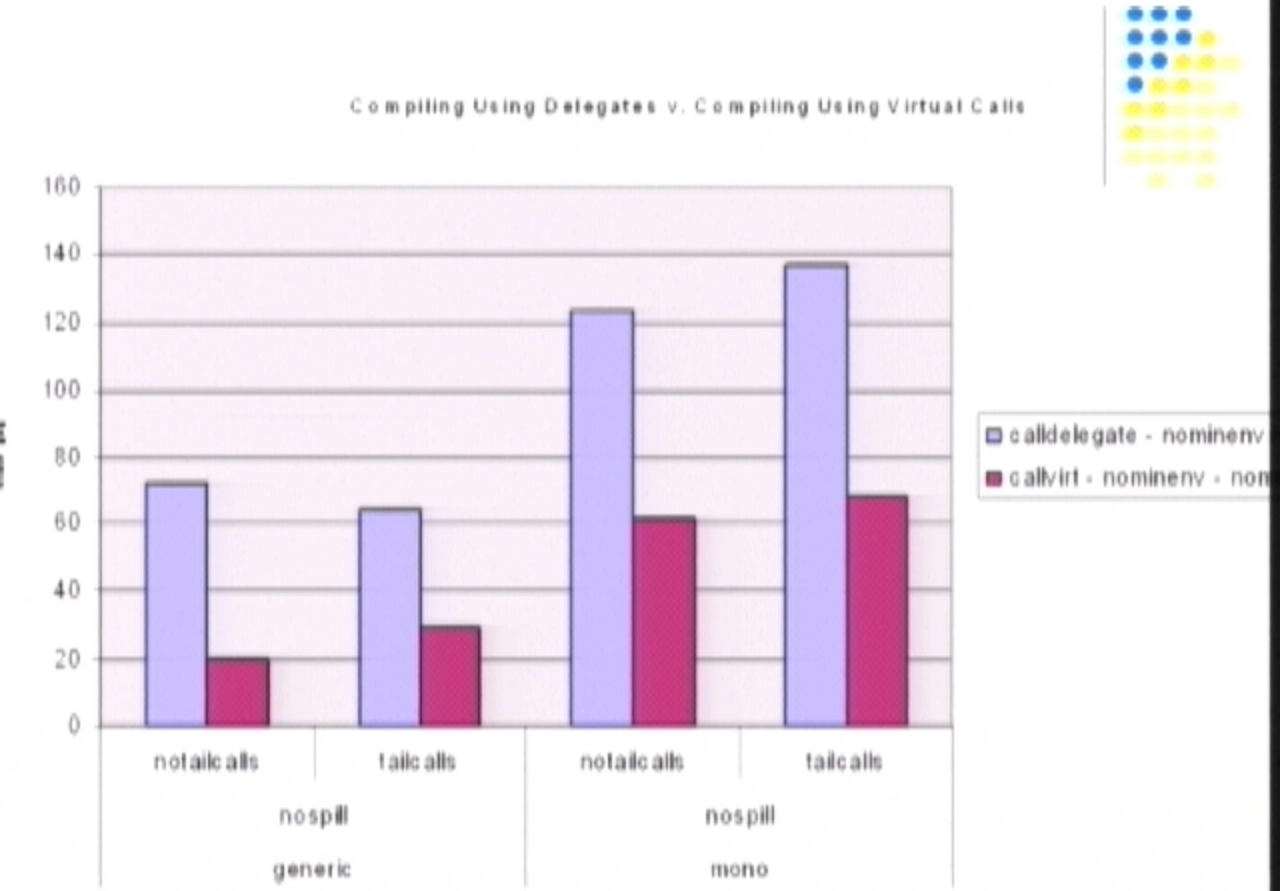
Haskell SML



# Simulated Performance Load

- Designed to be (very roughly) like the indirect calling load of a typical OCaml program:
  - 80% of closures take 1 argument
  - 15% take 2
  - rest take 3
  - 60% of closures have 0 free variables
  - 30% of closures have 1 free variable
  - 10% of closures have 2 free variables
  - All calls are indirect
  - Each closure used to create a varying number of function values
  - Each function value called a varying number of times
- BEST TIME =~ 11s


Compiling Using Delegates v. Compiling Using Virtual Calls
160
140
120
100
80
60
40
20
0
notailcalls
tailcalls
notailcalls
tailcalls
nospill
generic
nospill
mono
calldelegate - nominenv
callvirt - nominenv - non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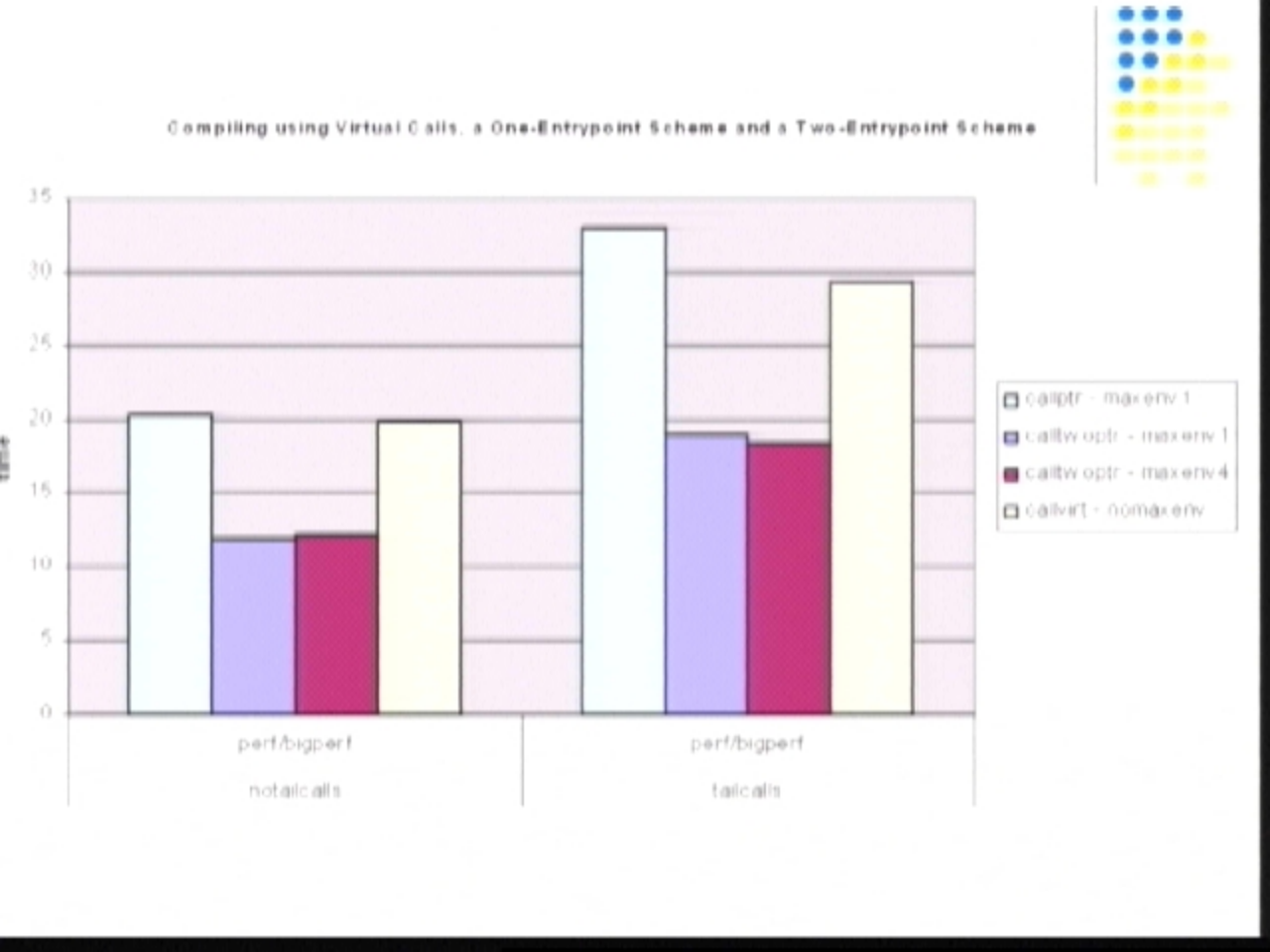
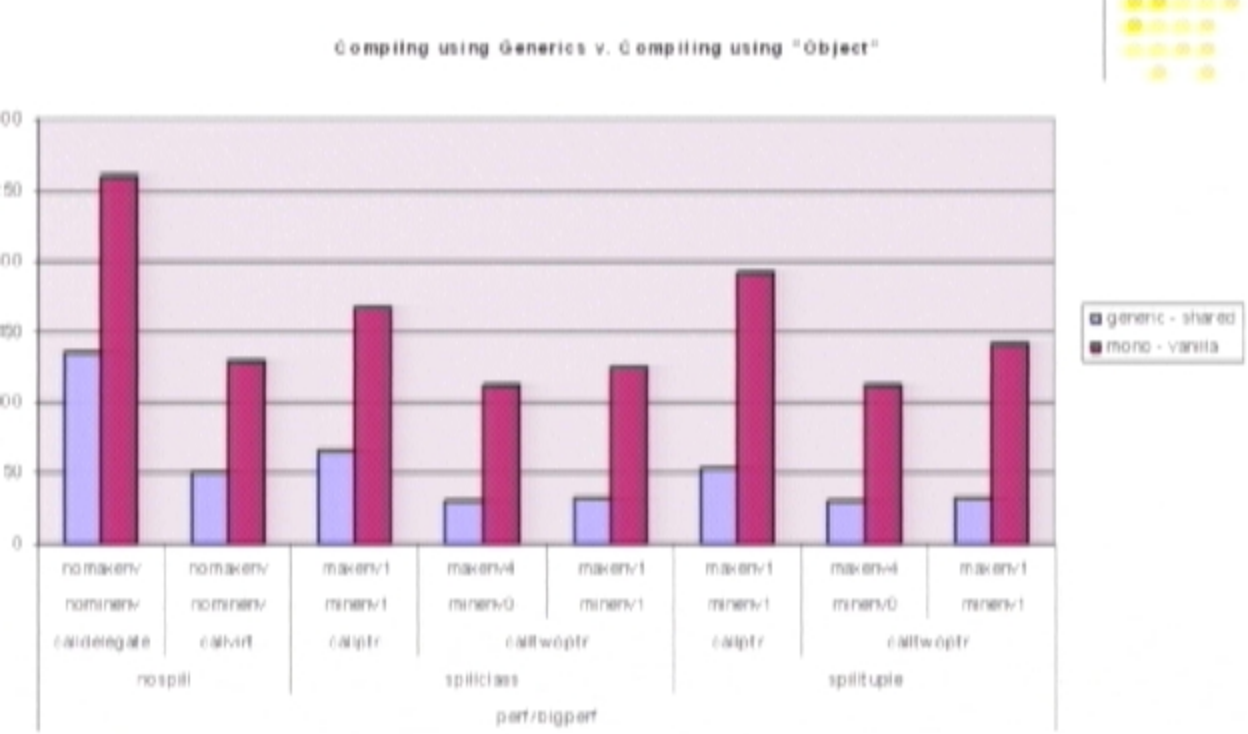
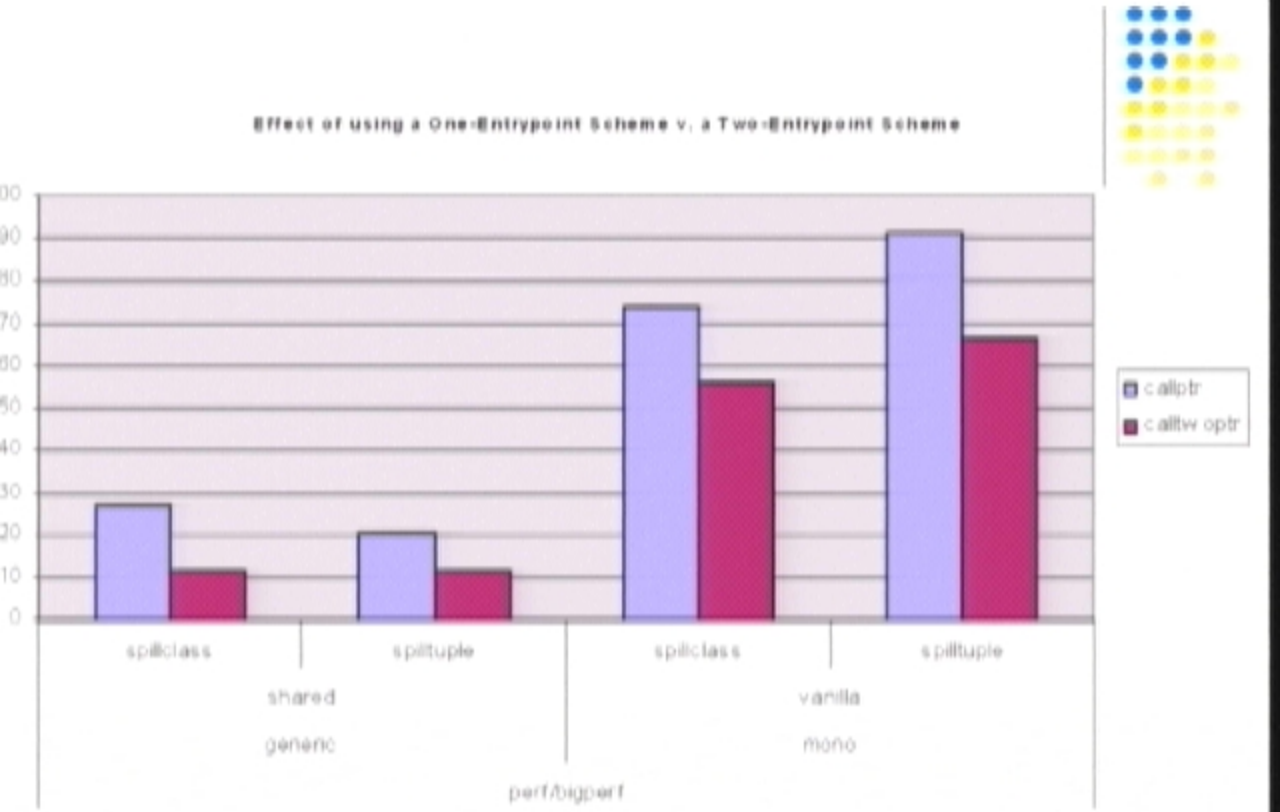
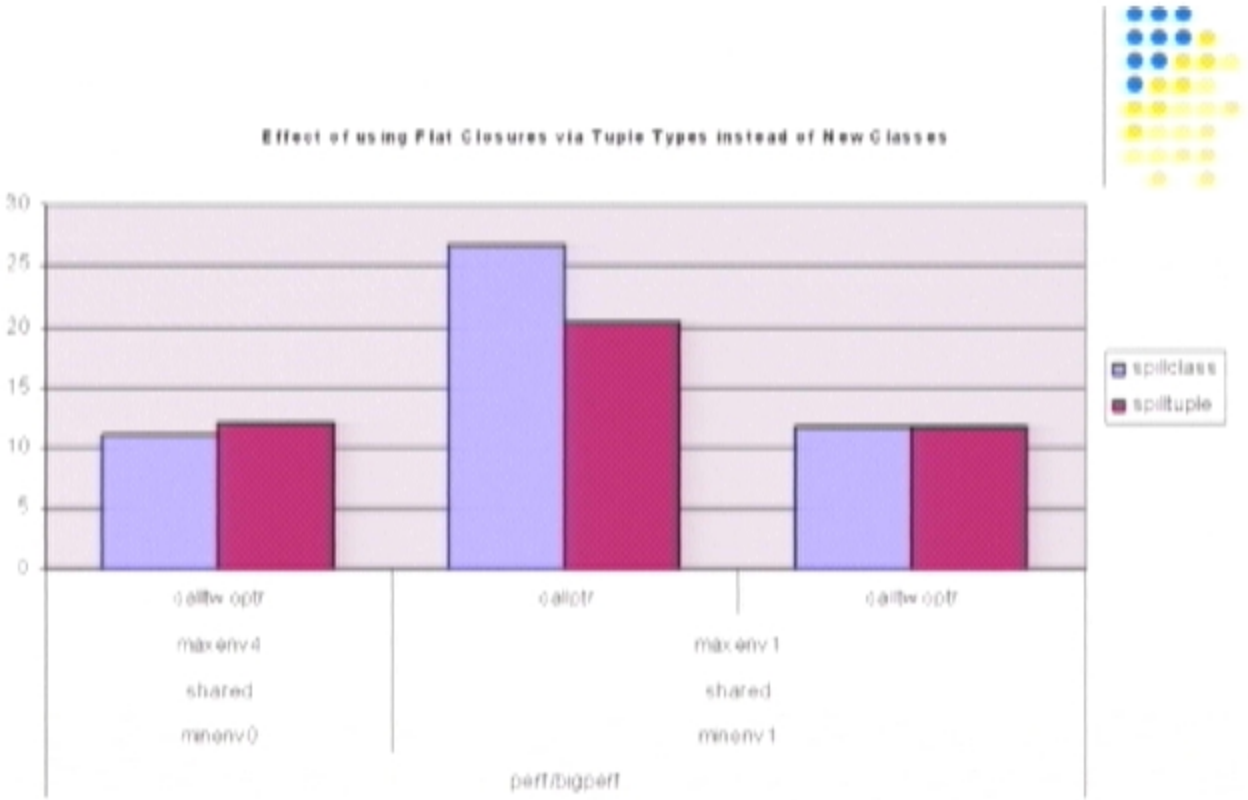
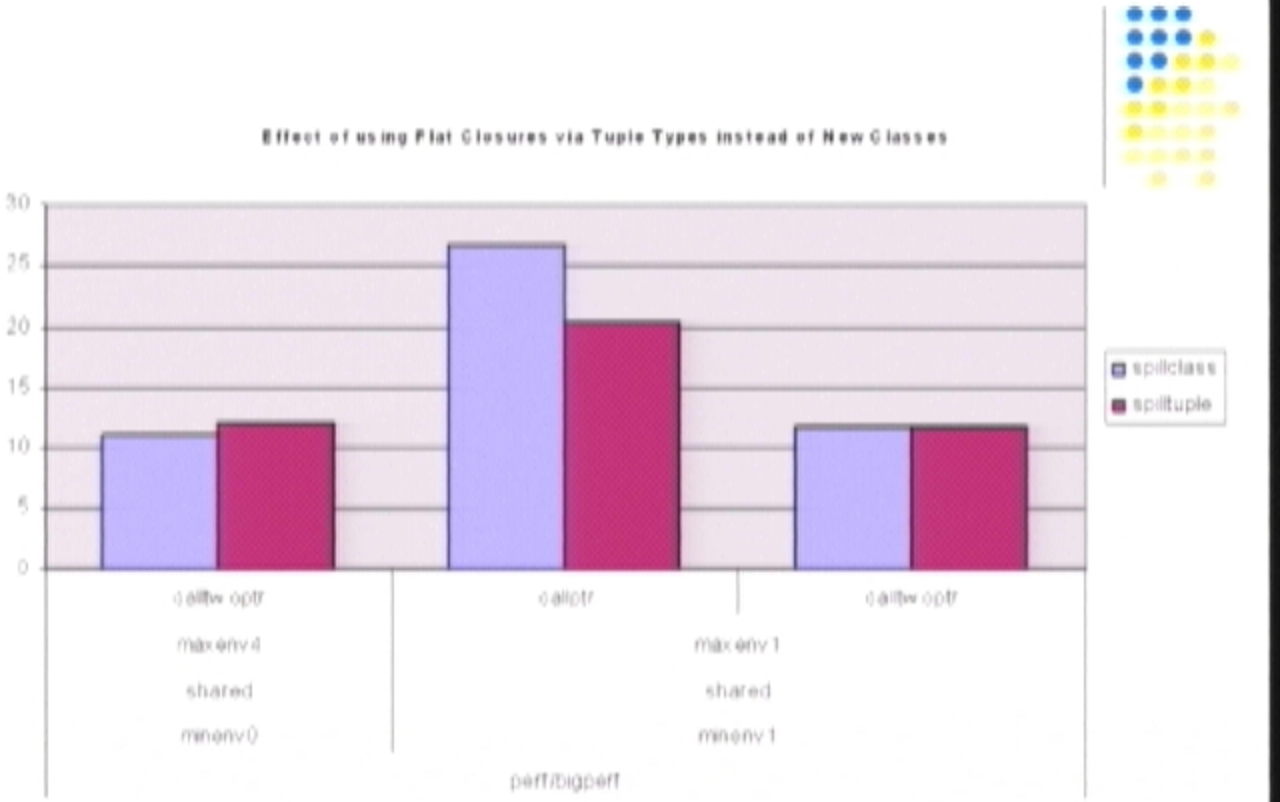

Compiling using Virtual Calls, a One-Entrypoint Scheme and a Two-Entrypoint Scheme
35
30
25
20
15
10
5
0
callptr - maxenv 1
callfw optr - maxenv 1
callfw optr - maxenv 4
callvirt - nomaxenv
perf/bigperf
notailcalls
perf/bigperf
tailcalls


Compiling using Generics v. Compiling using "Object"
00
50
00
50
00
50
0
generic - shared
mono - vanilla
nomakenv
nomnenv
/aldelegate
nomakenv
nomnenv
/allvirt
makenv/1
mnenv/1
/allptr
makenv/4
mnenv/0
makenv/1
mnenv/1
/alltwoptr
makenv/1
mnenv/1
/allptr
makenv/4
mnenv/0
makenv/1
mnenv/1
/alltwoptr
nospli
splitclass
splitupie
perf/bigperf


Effect of using a One-Entrypoint Scheme v. a Two-Entrypoint Scheme
callptr
callvw optr
spliclass
spiltuple
spliclass
spiltuple
shared
generic
vanilla
mono
perf/bigperf


Effect of using Flat Closures via Tuple Types instead of New Classes
30
25
20
15
10
5
0
splclass
spltuple
callfw optr
callctr
callfw optr
max env 4
shared
min env 0
max env 1
shared
min env 1
perf/bigperf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25
20
15
10
5
0
spillclass
spilltuple
callfw optr
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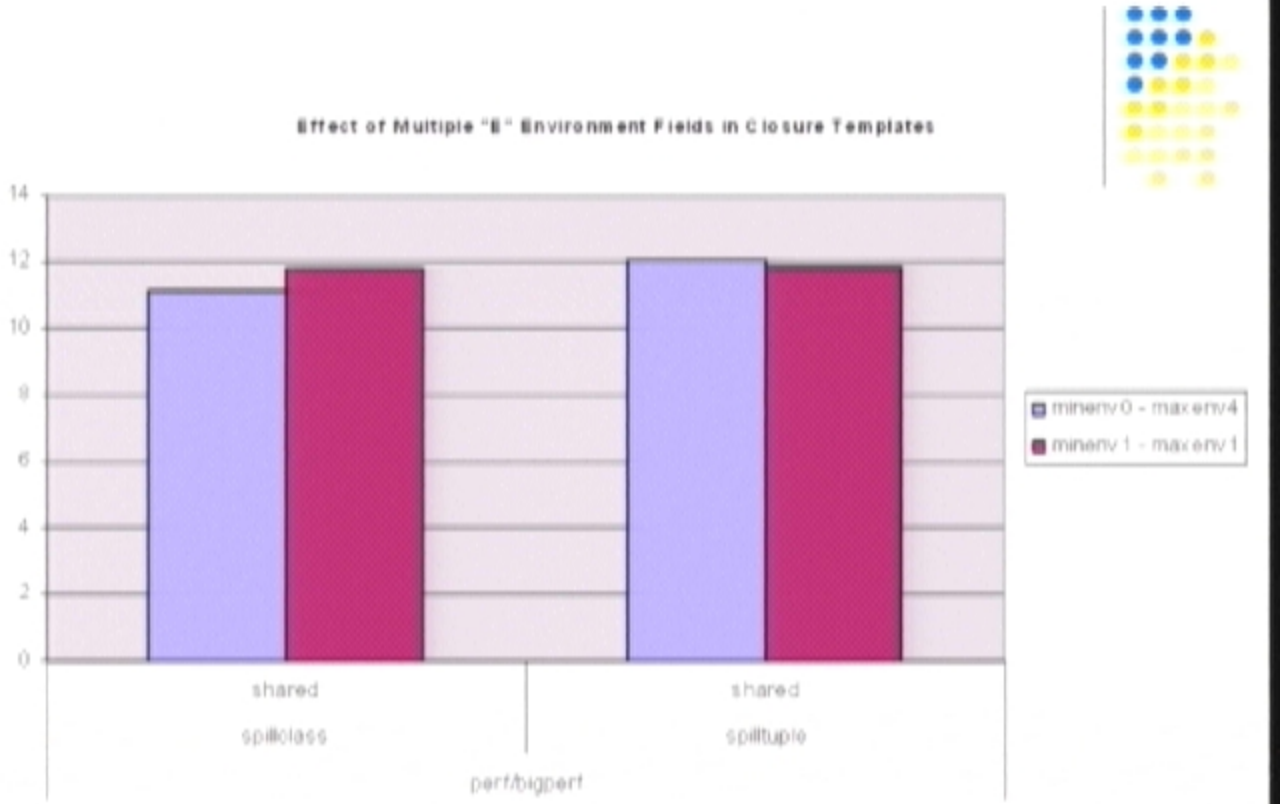
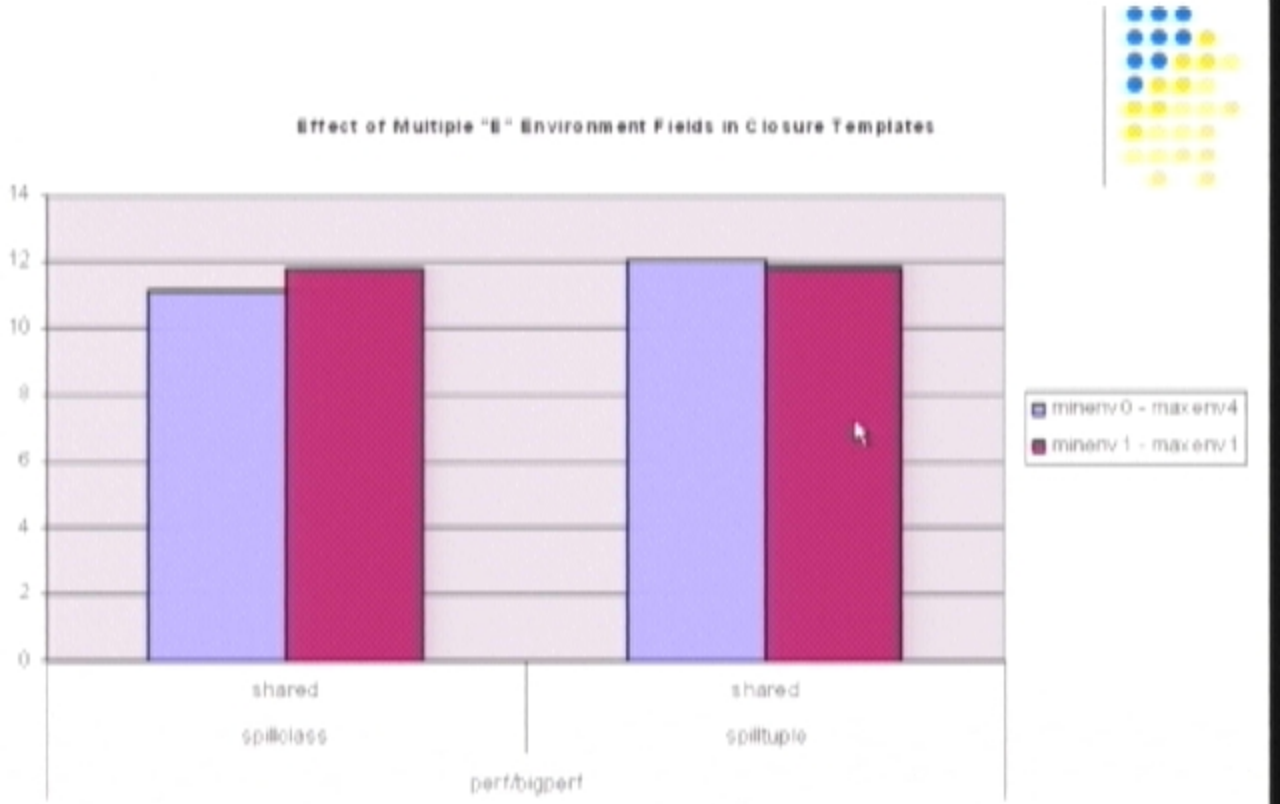
max env 4
max env 1
shared
shared
min env 0
min env 1
perf/bigperf


Effect of Multiple "E" Environment Fields in Closure Templates
14
12
10
8
6
4
2
0
shared
spillclass
shared
spilltuple
perf/bigperf
minenv 0 - maxenv 4
minenv 1 - maxenv 1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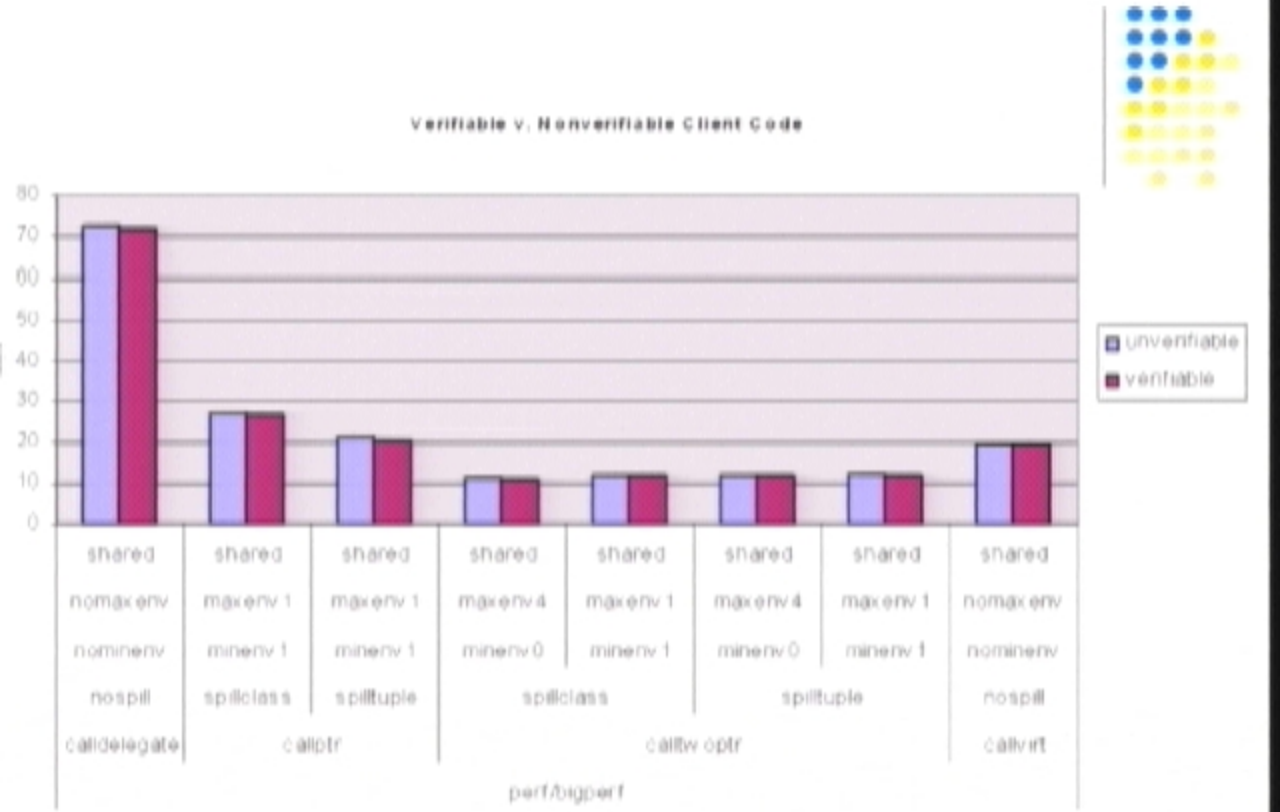
Verifiable v. Nonverifiable Client Code
80
70
60
50
40
30
20
10
0
unverifiable
verifiable
shared
nomaxenv
nominenv
nospill
callidelegate
shared
maxenv 1
minenv 1
spillclass
shared
maxenv 1
minenv 1
spilltuple
callptr
shared
maxenv 4
minenv 0
shared
maxenv 1
minenv 1
spillclass
shared
maxenv 4
minenv 0
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minenv 1
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maxenv 1
minenv 1
spilltuple
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shared
maxenv 4
minenv 0
shared
maxenv 1
minenv 1
spillclass
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# Conclusions

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2. V1 Tailcalls suck
3. Generics are an extremely useful compilation device
4. Multiple entry points are feasible and worth it
5. Flat closures are feasible and worth it
6. Multiple environment slots are not worth it

7. A library-based approach is feasible

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# Related Concepts

- Classes/Objects
  - Context is explicit (the fields)
  - Contain much more: multiple methods, static methods, reflection, ...
- Java Inner Class: "class in a context"
  - Context is explicit
  - Class can have many methods
- C# Delegates
  - Context is explicit
  - Code and data are tied
  - Also asynchronous invocation etc.
- Method pointer
  - Object + pointer to method
  - = Unboxed Delegate
  - Full closures are much more useful

# Looking Forward

Ways ahead:

1. Thoroughly investigate performance for real programs, plus a range of languages

2. V2 delegates =

V1 delegates
+
Basic perf improvements
+
Delegate to static, external methods
+
Environments inline in delegate
+
Multiple entry points

# Summary

Problems:

1. Reusing our generics design gives exact runtime type semantics.

2. The most efficient standardized encoding/shared library of closures is quite complex.

Future research:

1. Thoroughly investigate performance for closures

2. Perhaps propose standard encodings for other constructs

# Questions?

# Runtime Verification and .NET

Michael Barnett
Wolfram Schulte
Foundations of Software Engineering

# Testing and Verification?

"Computer Science is akin to astronomy and astrology, but it lacks the precision of the former and the popularity of the latter."

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  - Programmers write exception handling
  - Programmers write code!

# It's the level, stupid…

- Specifications would be more useful if they were:
  - At a higher level
  - Available separate from source code
  - Enforceable

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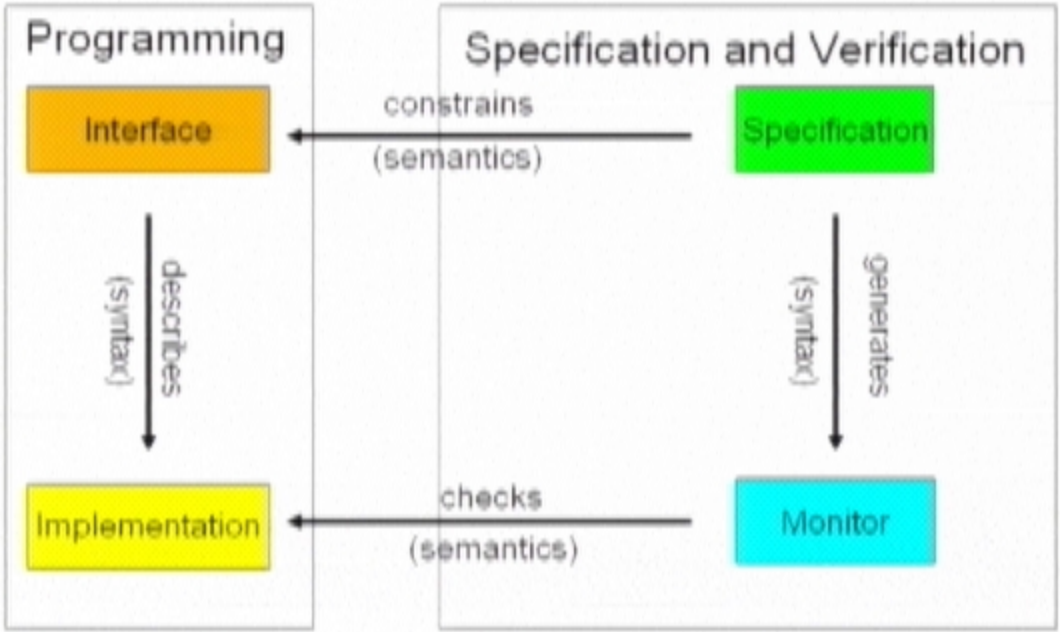
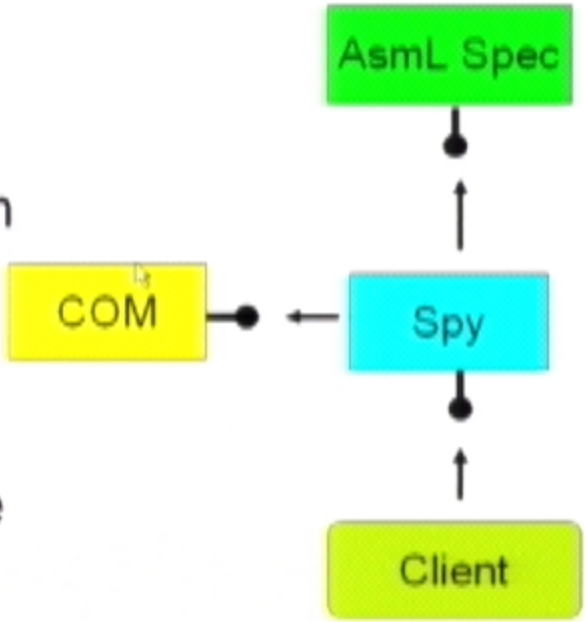
i.e., executable!

# The Big Picture

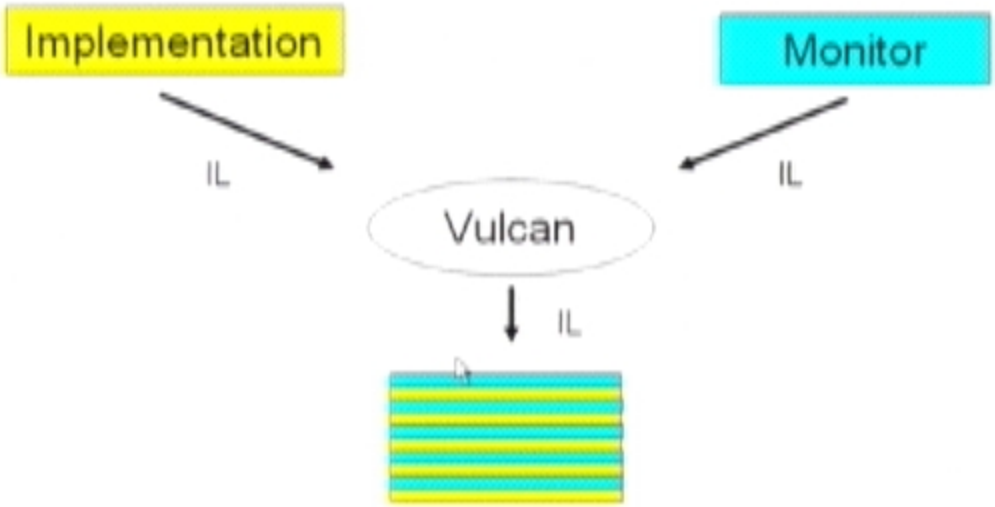


# Previously…

+ Observational equivalence
+ No instrumentation required
- Non-determinism
- Callbacks
- State equivalence



# Tighter Integration: .NET



# (Trivial) Example

```
interface IMath {
  double sqrt(double x);
  ...
}
```

```
class CMath : IMath {
  double sqrt(double x)
    { ... }
  ...
}
```

```
class IMath_Contract : CMath {
  bool sqrt_pre(double x)
    { x >= 0; }
  bool sqrt_post(double x)
    { result * result == x; }
}
```

# Monitored Implementation

```
class CMath {

  double sqrt(double x)
   { double result;
     assert(x >= 0);
     modified body
     assert(result*result == x);
     return result;
   }
}
```

# Monitor Language

```
class I_Contract {
  bool f_pre(...) { }
  bool f_post(...) { }
  bool f_classInvariant(...) { }
  Object f_exception(...) { }
}
```

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# What to specify?

- Properties
  - Pre-/post-conditions
- Calling protocols
  - Required method calls: *mandatory calls*
- Model State
  - Required persistence: *objects*
- Exceptions

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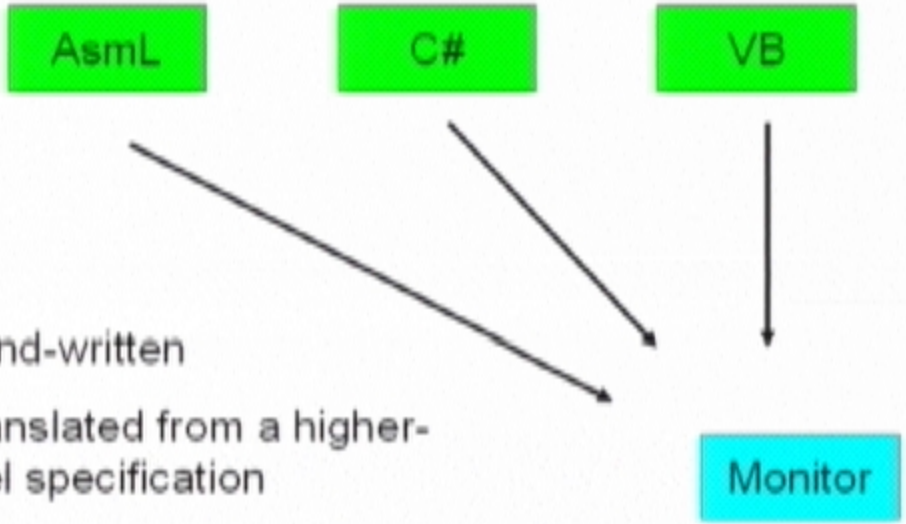
# Monitors


AsmL
C#
VB
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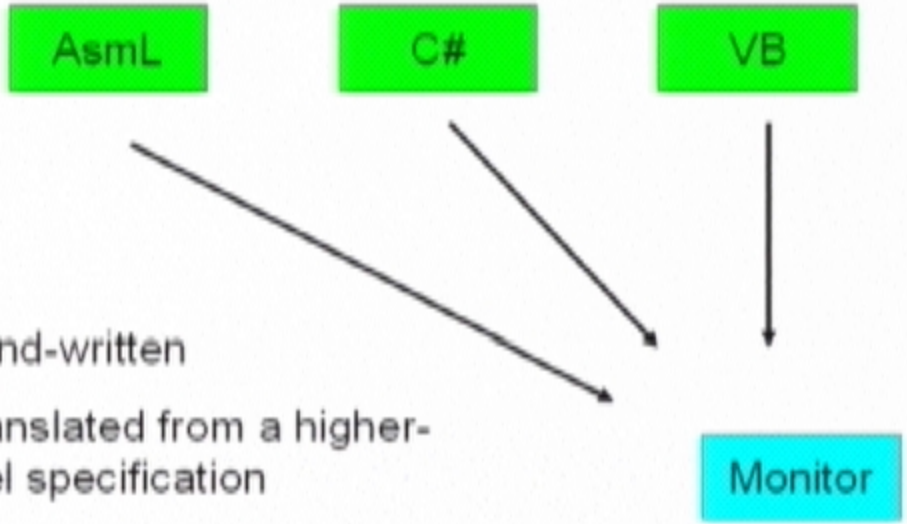
AsmL
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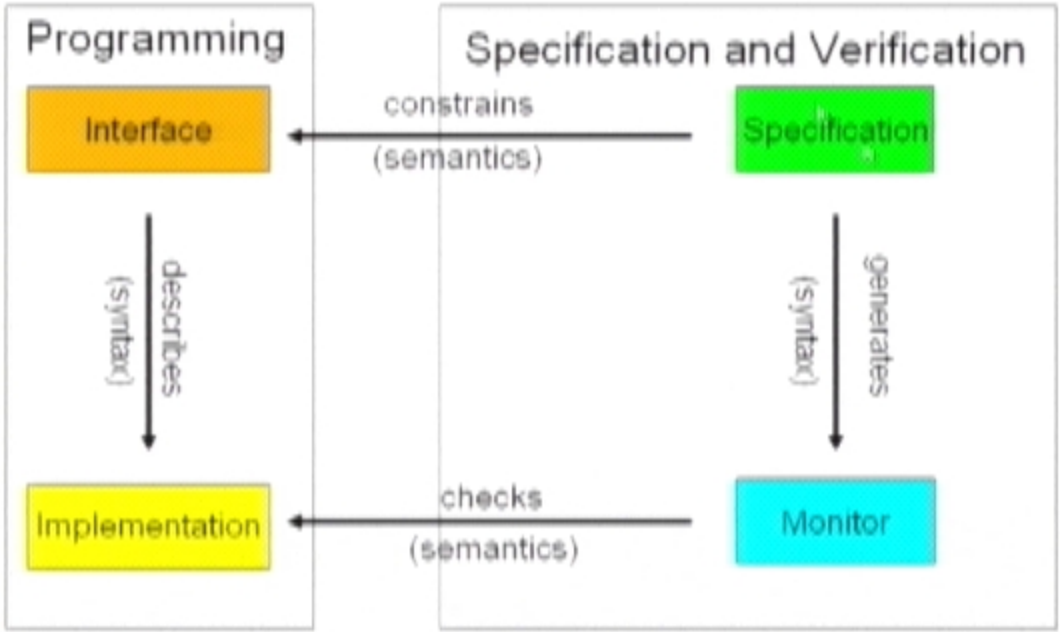
Monitor

# AsmL: Microsoft's ASM-Language

- A powerful specification language:
  - Based on ASMs
  - Readable, executable, testable
  - Combines mathematical, object-oriented, component-oriented approaches
  - Integrated into VS6 (working on VS.NET)
  - Literate style: Word and XML

# The Big Picture



# AsmL: Microsoft's ASM-Language

- A powerful specification language:
  - Based on ASMs
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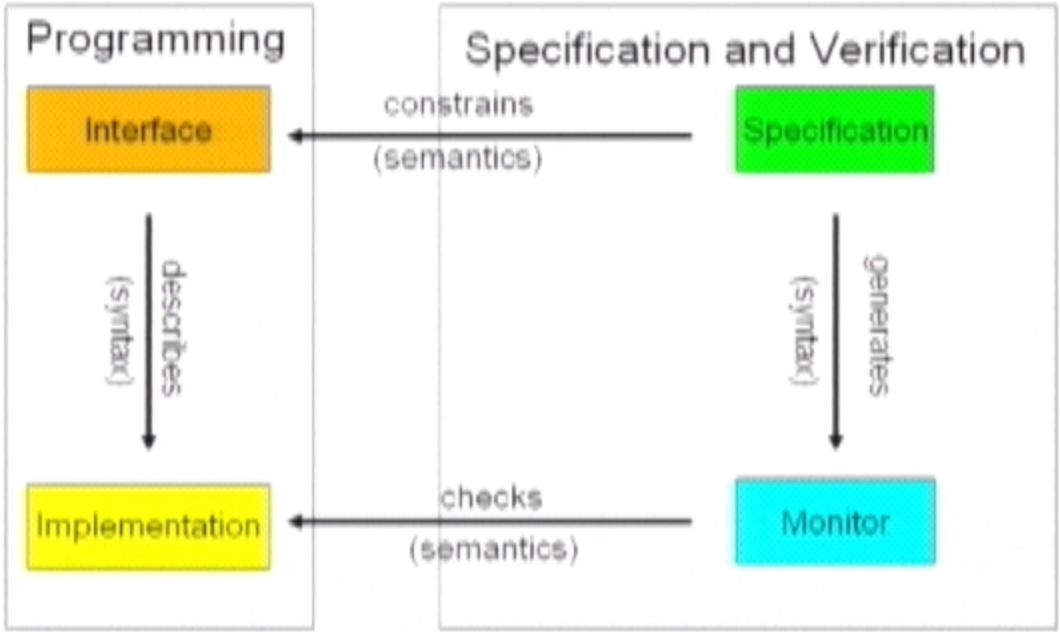
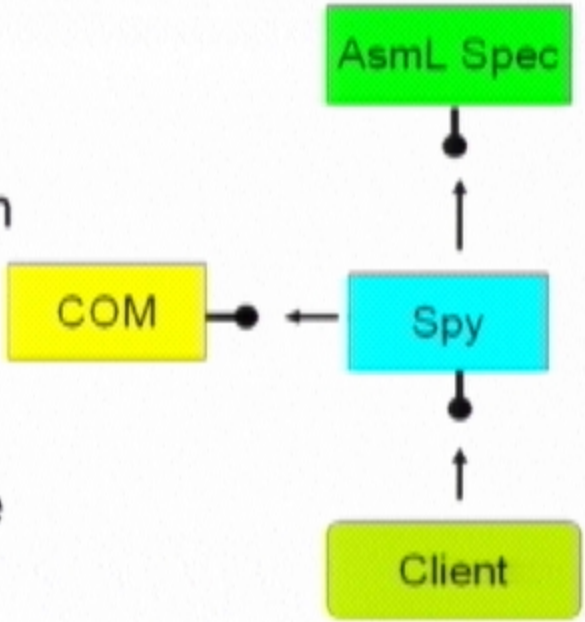


# Previously…

+ Observational equivalence
+ No instrumentation required
- Non-determinism
- Callbacks
- State equivalence



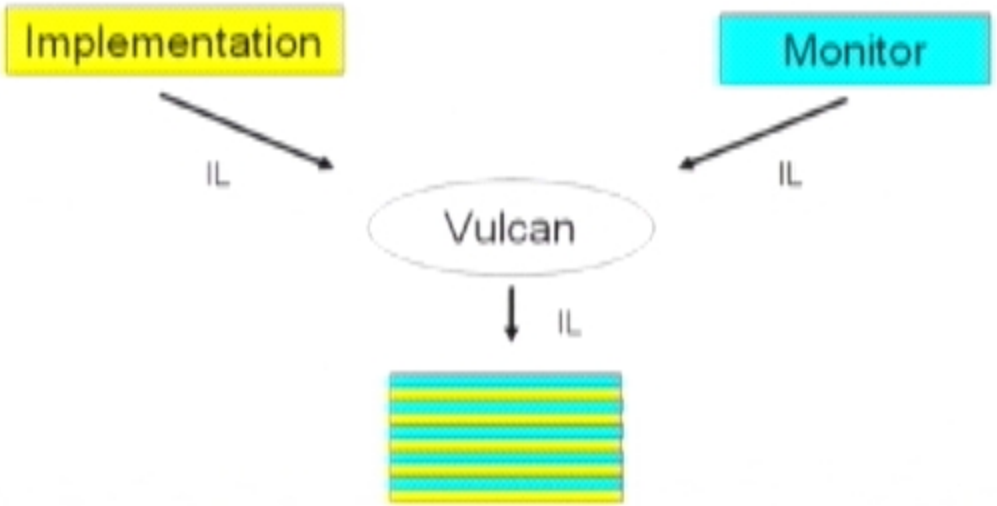
# (Trivial) Example

```
interface IMath {
  double sqrt(double x);
  ...
}
```

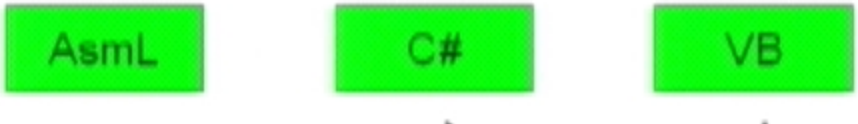
```
class CMath : IMath {
  double sqrt(double x)
    { ... }
  ...
}
```

```
class IMath_Contract : CMath {
  bool sqrt_pre(double x)
    { x >= 0; }
  bool sqrt_post(double x)
    { result * result == x; }
}
```

# Tighter Integration: .NET



# Monitors




- Hand-written
- Translated from a higher-level specification

Monitor

# (Trivial) Example

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interface IMath {
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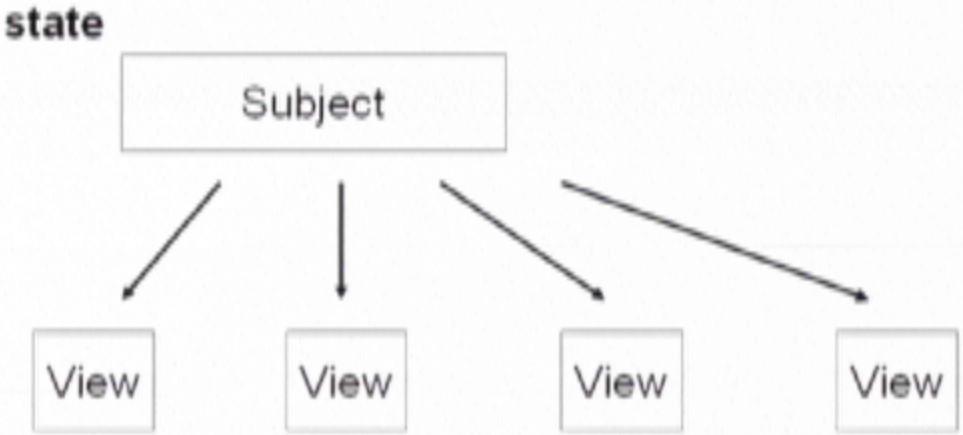
# Subject/View



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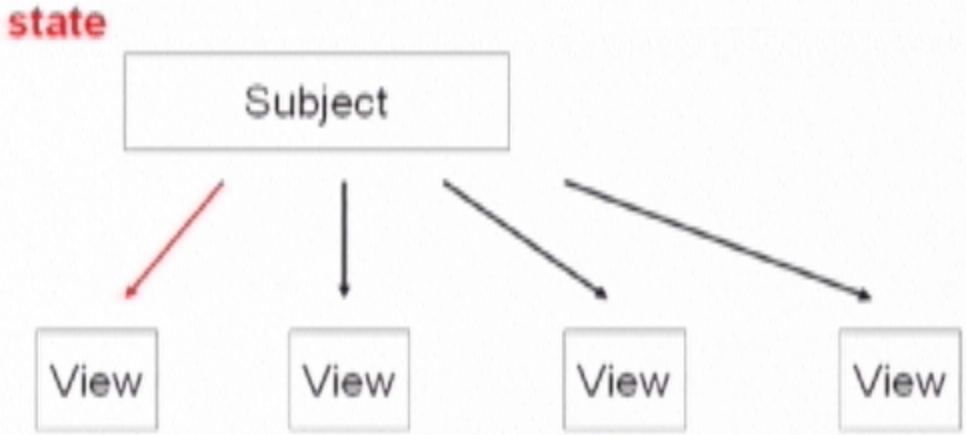

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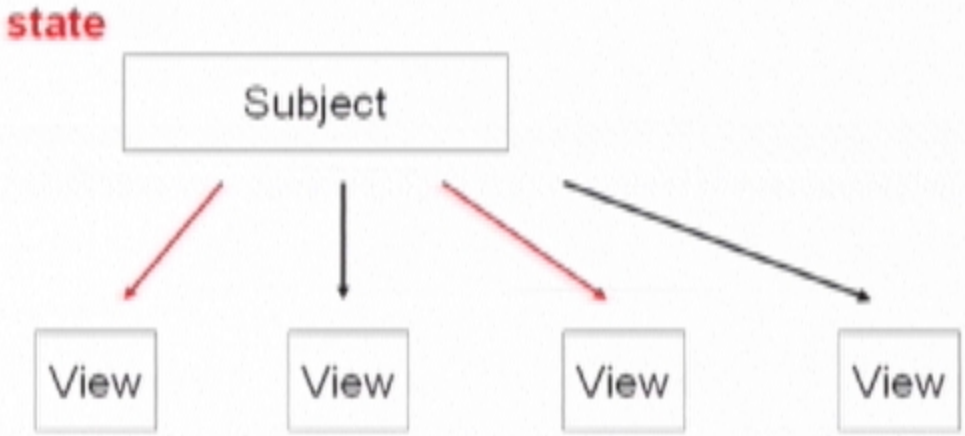
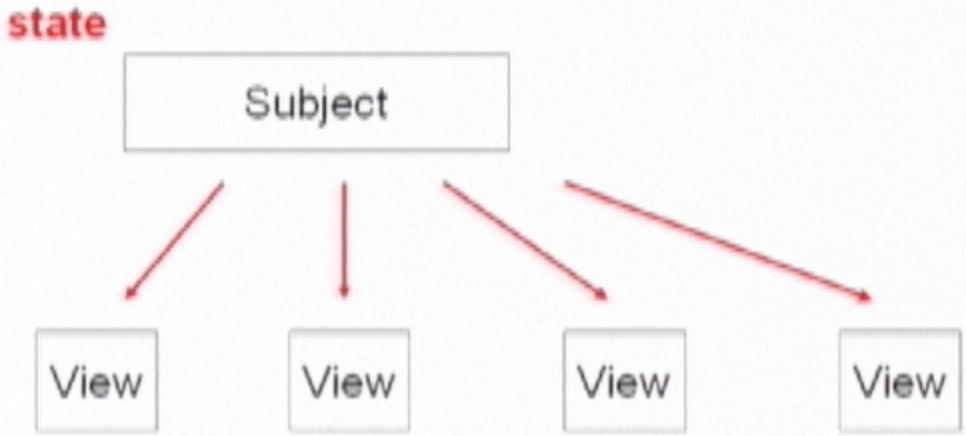


# Subject/View



# Subject/View in AsmL

```
class Subject[T]
  state as T
  views as Set[IView]

  Get() as T =  state

  Set(x as T) =
    machine
      state := x
    step
      forall v in views do
        v.Update()
```

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Notify **after** update

Parallel **forall:** all views see same state

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    step
      forall v in views do
        v.Update()
```

Notify **after** update

Parallel **forall:** all views see same state

Mandatory call: once per view

# Deriving the Monitor from AsmL

```
Set(x as T) =
  machine  state := x
  step     forall v in views do v.Update()
```

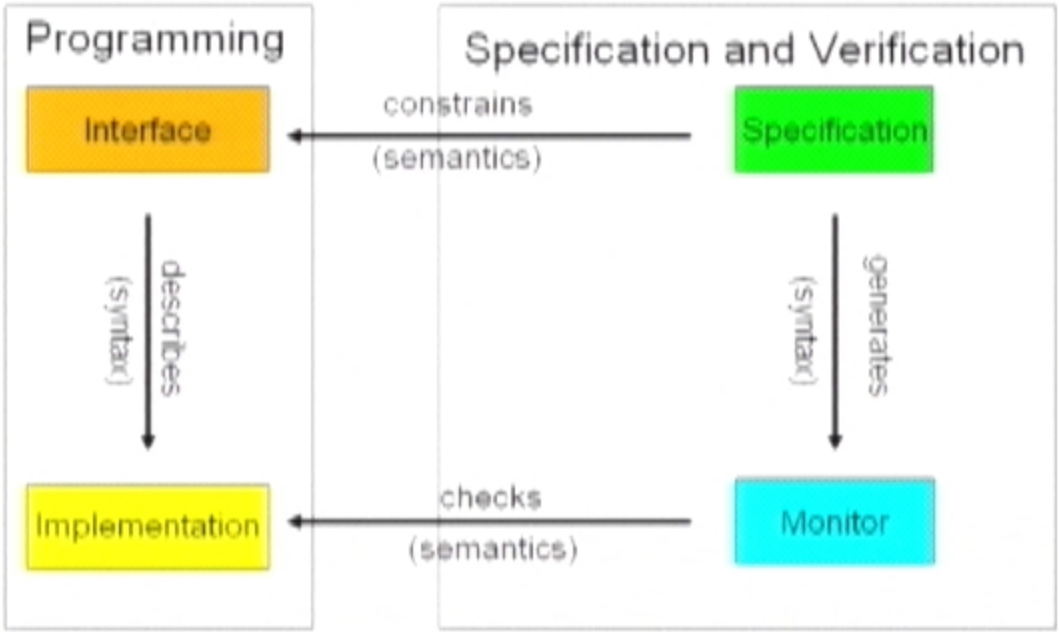
```
Set_pre() { mcalls = { v.Update | v in views }; }
Set_body() { state = x; }
Set_post() { assert(mcalls == {}); }

Update_pre() { assert(state == x); }
Update_post() { mcalls.remove(v.Update) }
```

# Summary: Runtime Verification

- Monitor design can be used for arbitrary purposes
- Monitor is generated automatically from AsmL
  - Can be added incrementally
  - Does not require model checking, theorem proving, etc.

http://asml

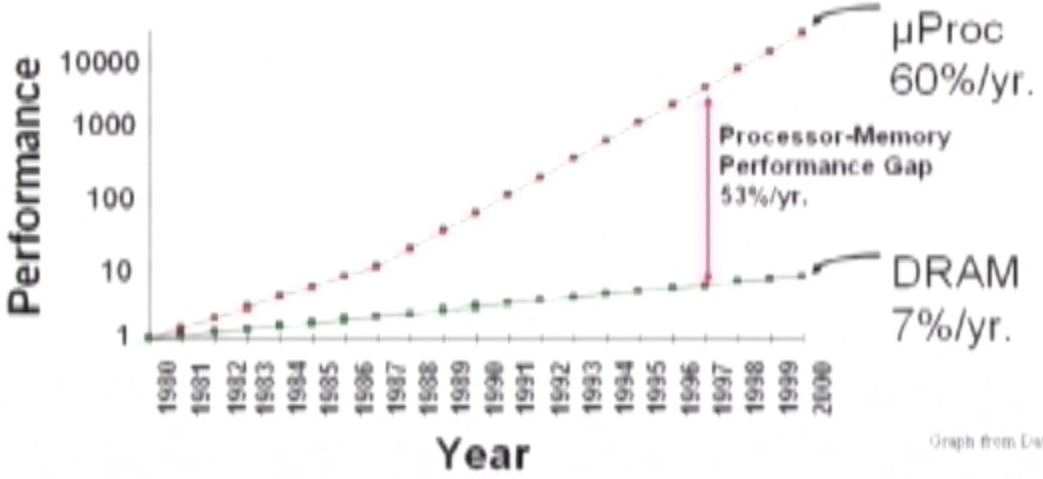
# The Big Picture



# Using Garbage Collection to Improve Program Data Locality

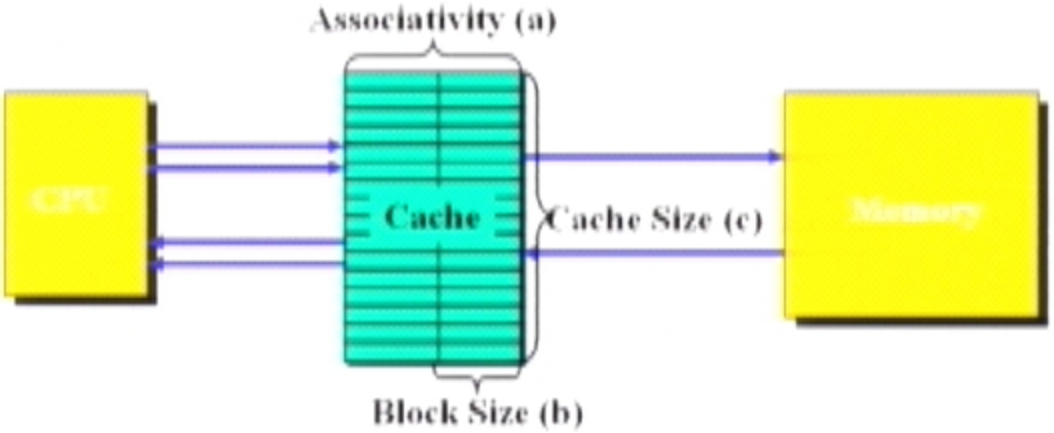
Trishul Chilimbi
PPRC, Performance Monitoring & Analysis
MS Research
http://research.microsoft.com/~trishulc/Daedalus.htm

# Processor-Memory Imbalance

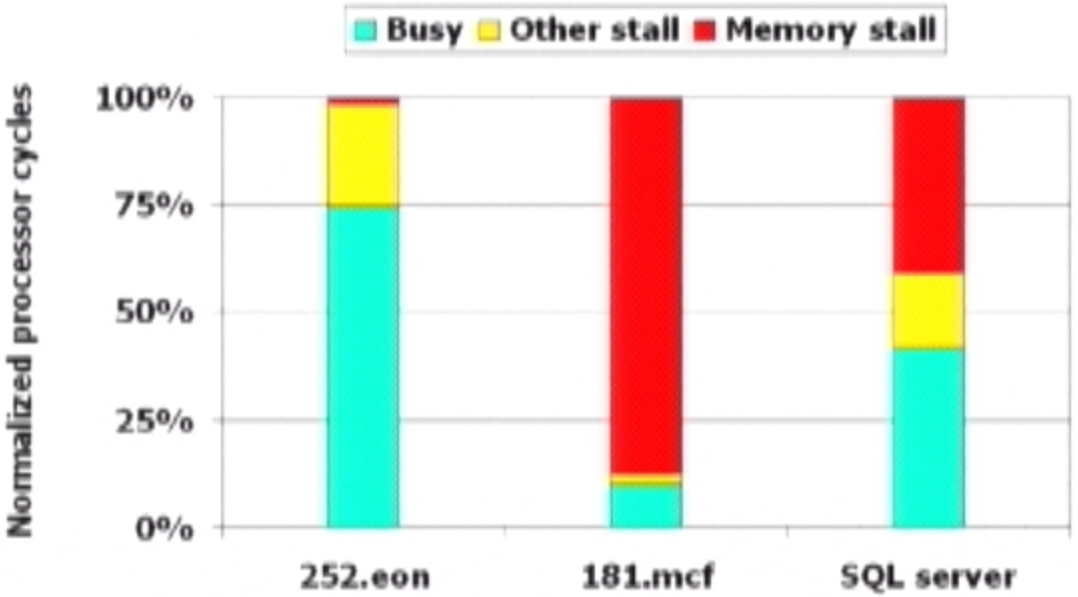



Graph from Dave Patterson

# Memory Cache: Reduce Latency



# Performance Impact



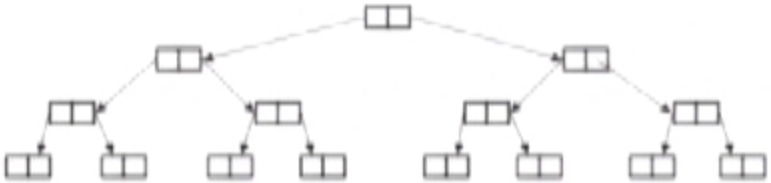
# Talk Outline

- Background
- Motivation
- GC for implementing cache-conscious data layouts
- Low-overhead data reference profiling
- Fast and accurate data layout determination

# Improving Memory System Performance

- New Hardware
  - Better caches
- New Software
  - Redesign code and structures
  - Cache-conscious algorithms
- Our approach: Improve locality of existing software automatically
  - Cache-conscious data layouts

# Cache-Conscious Data Layout



Random Layout

Cache Conscious

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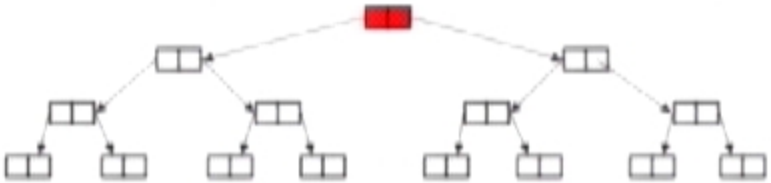

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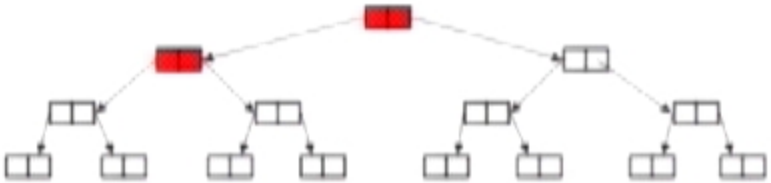

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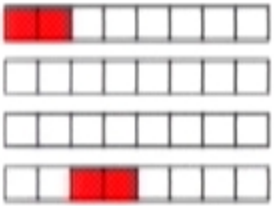

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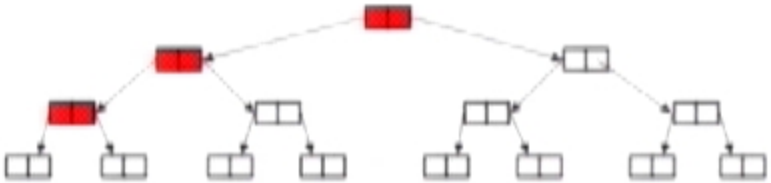
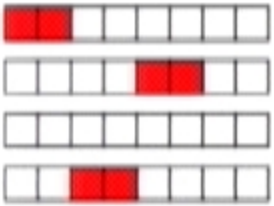


Random Layout



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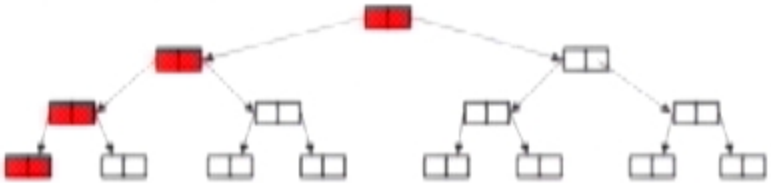

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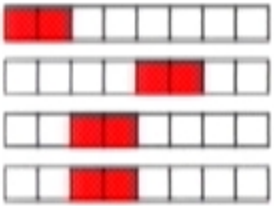

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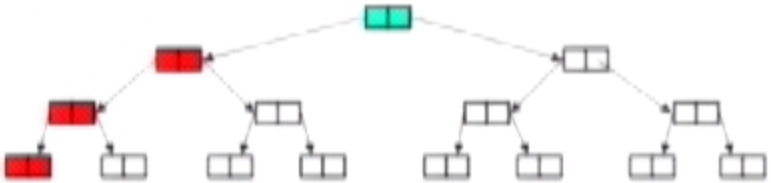

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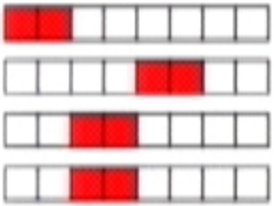

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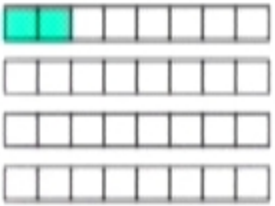

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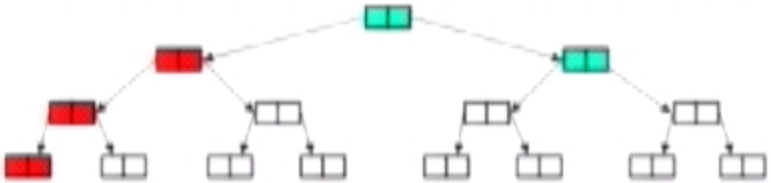

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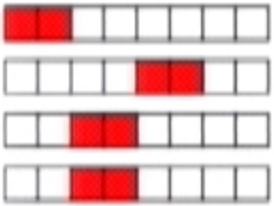

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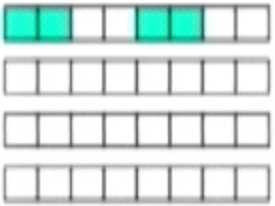

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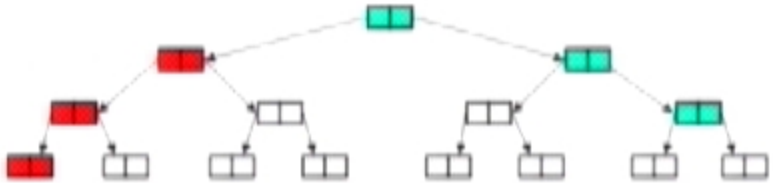

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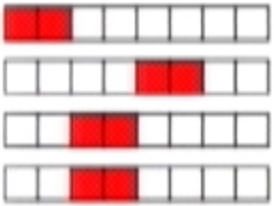

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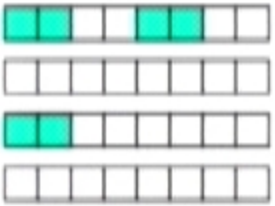

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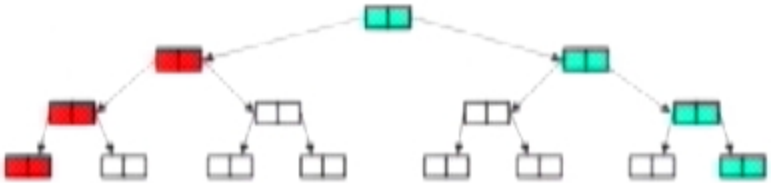

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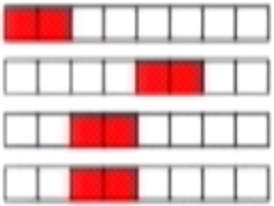

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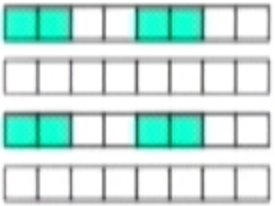


# Talk Outline

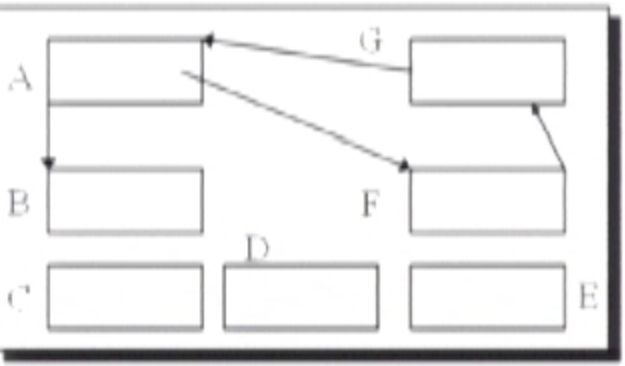
- Background and Motivation
- GC for implementing cache-conscious data layouts
  - Structure reorganization
  - Hot/cold splitting
  - Limitations
- Low-overhead data reference profiling
- Fast and accurate data layout determination

# Copying Garbage Collection

FROM space

TO space

Roots: A, C, E



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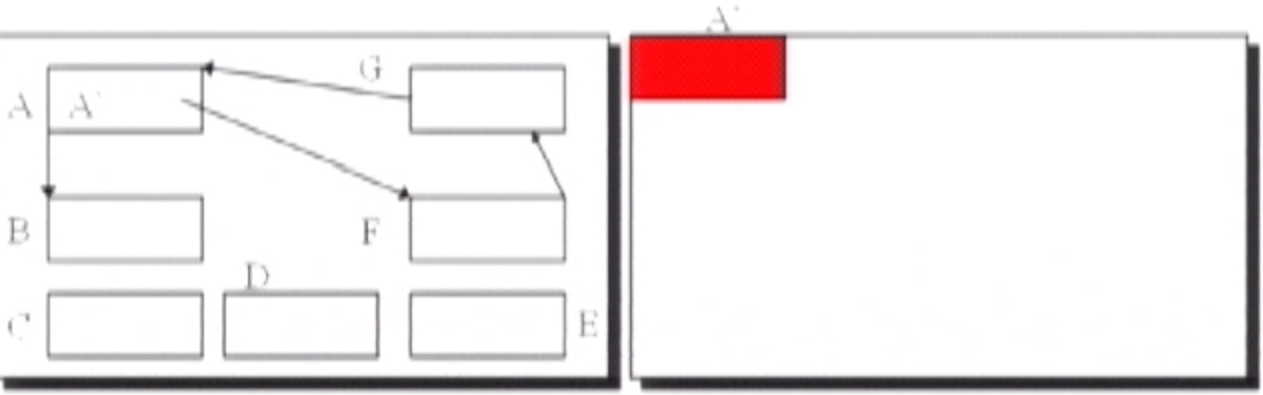

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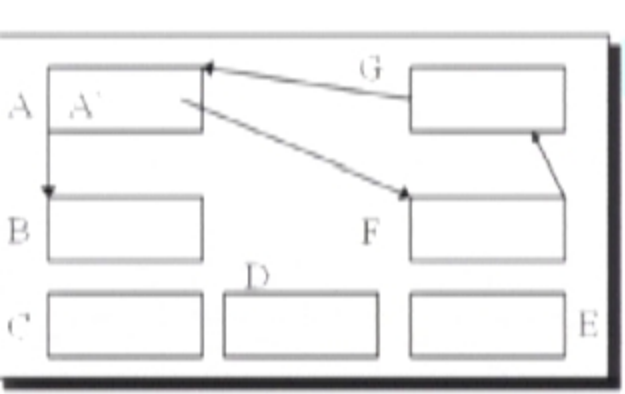


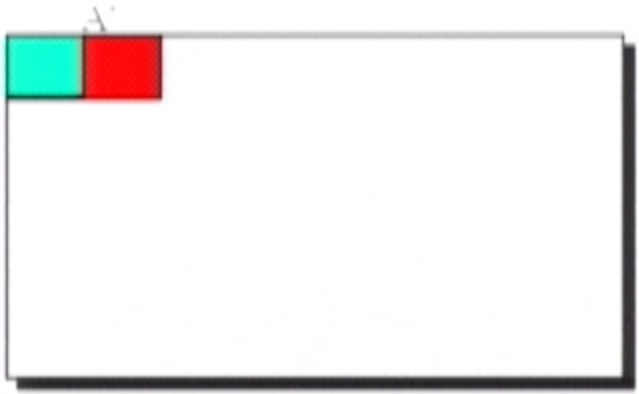

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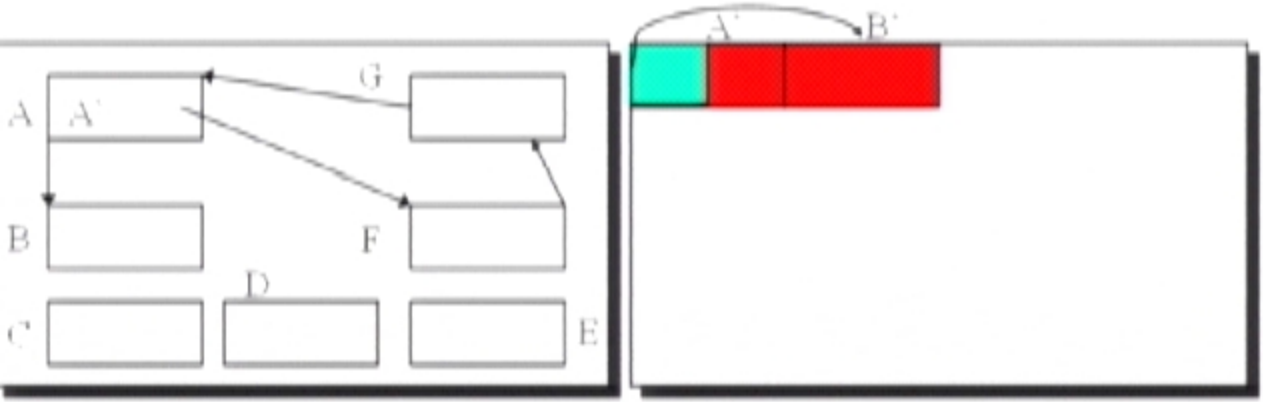

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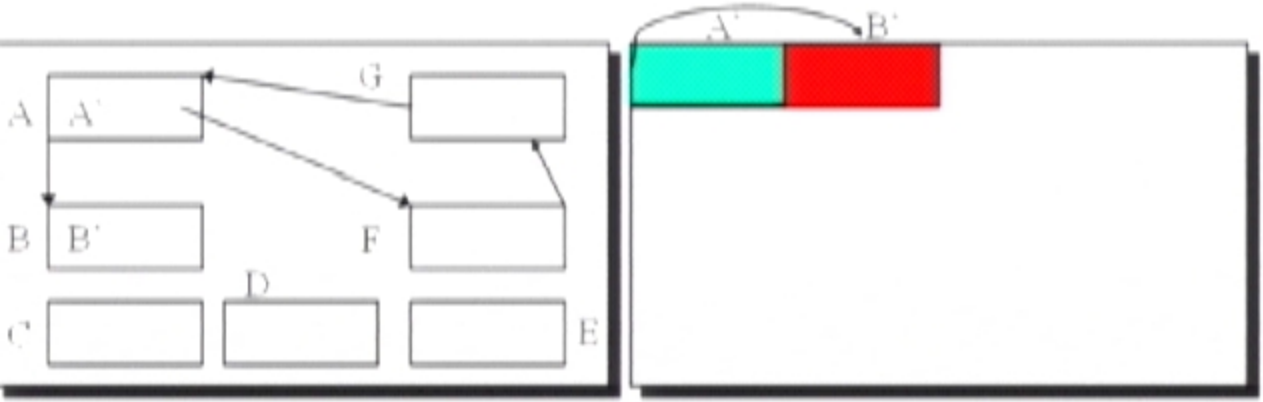

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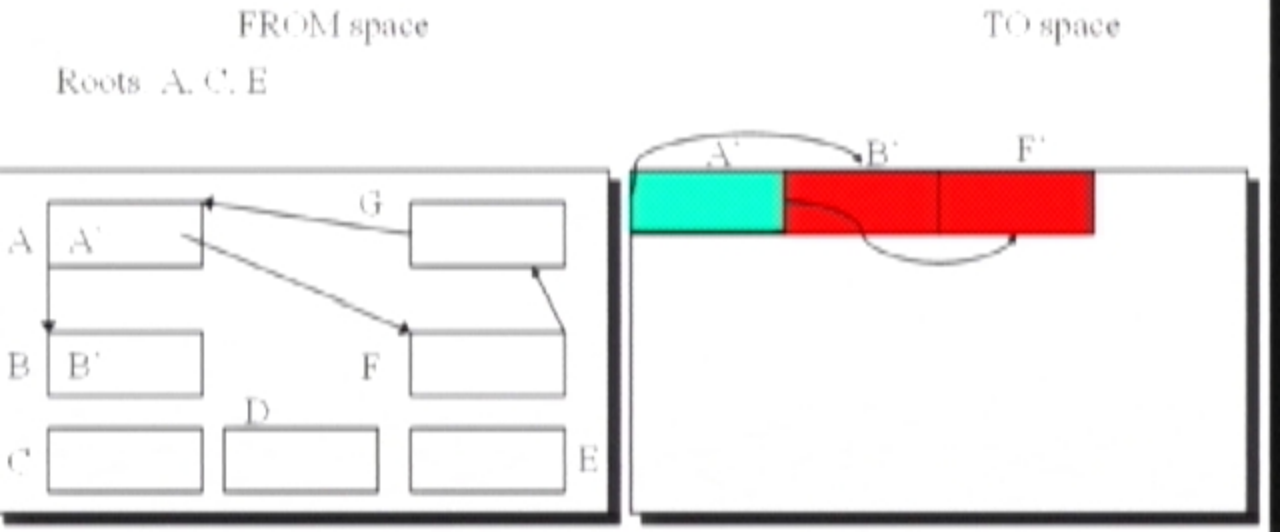

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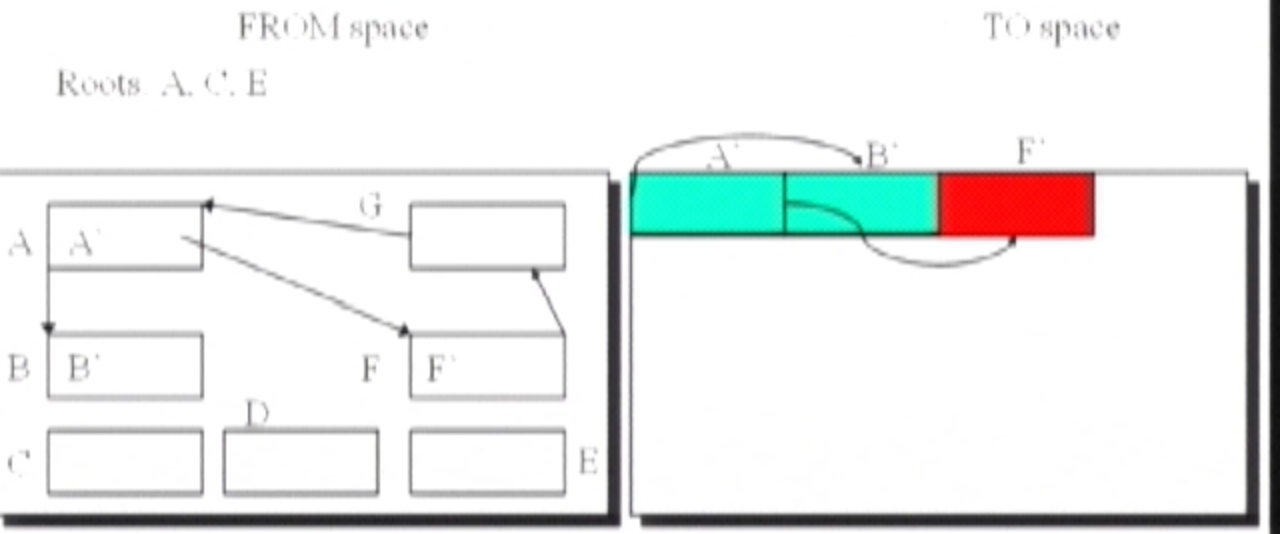

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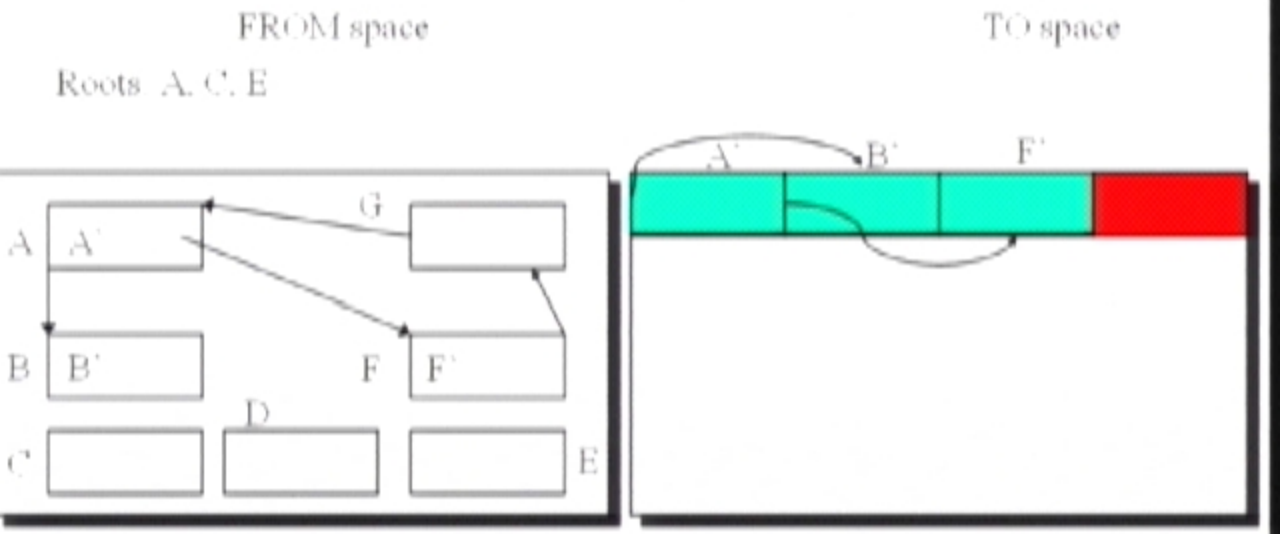

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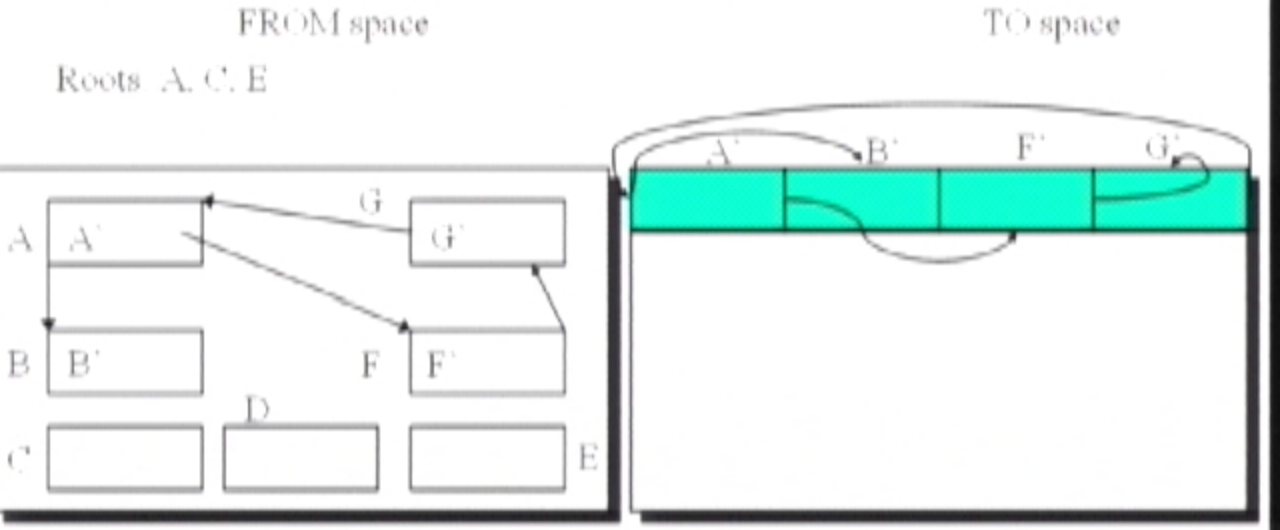

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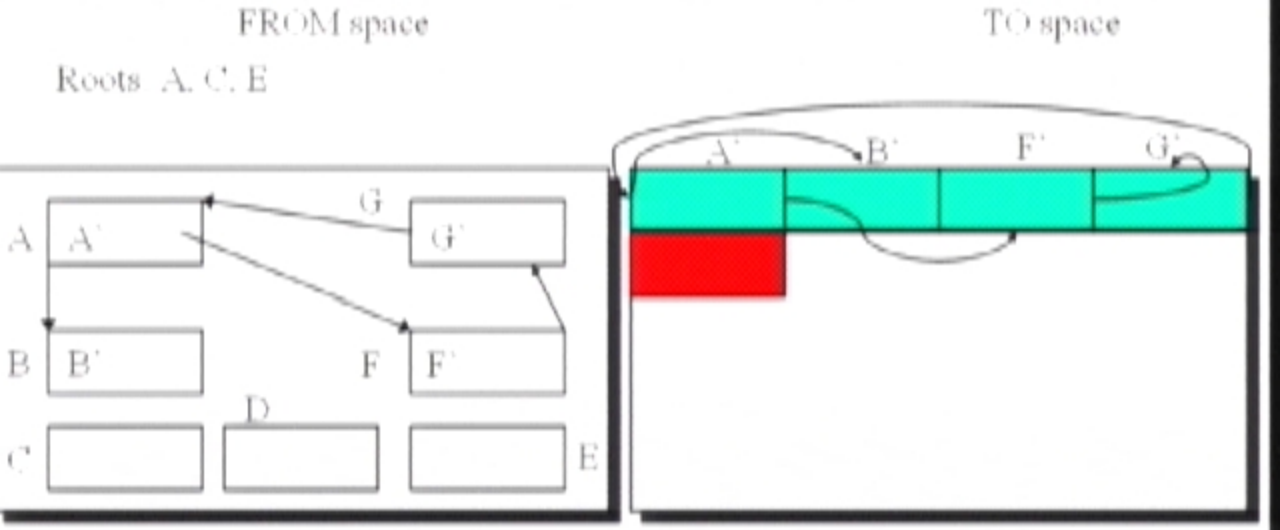
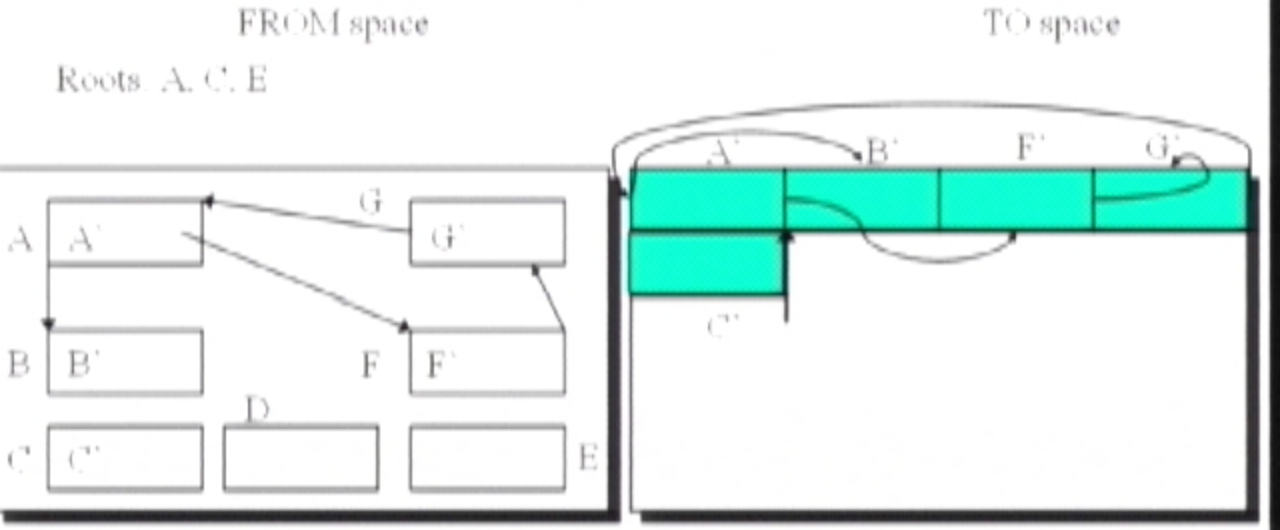


# Copying Garbage Collection



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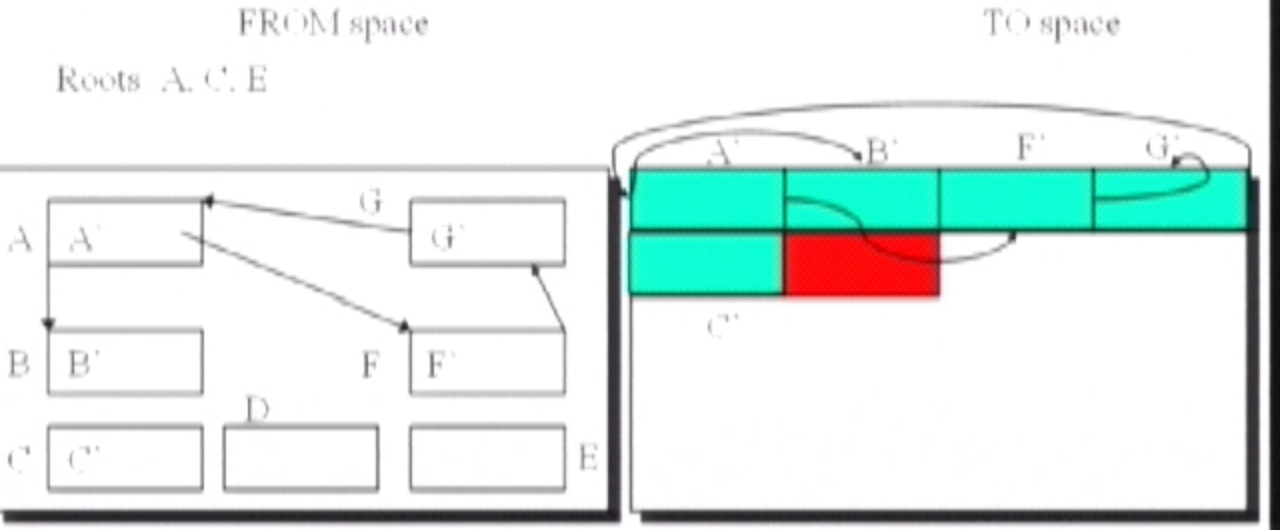

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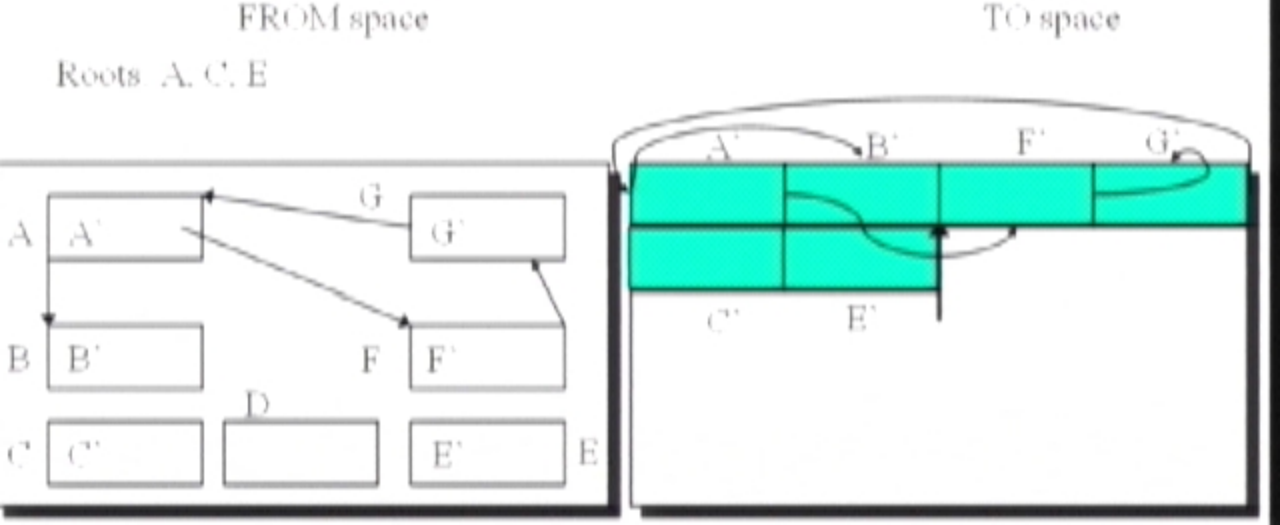

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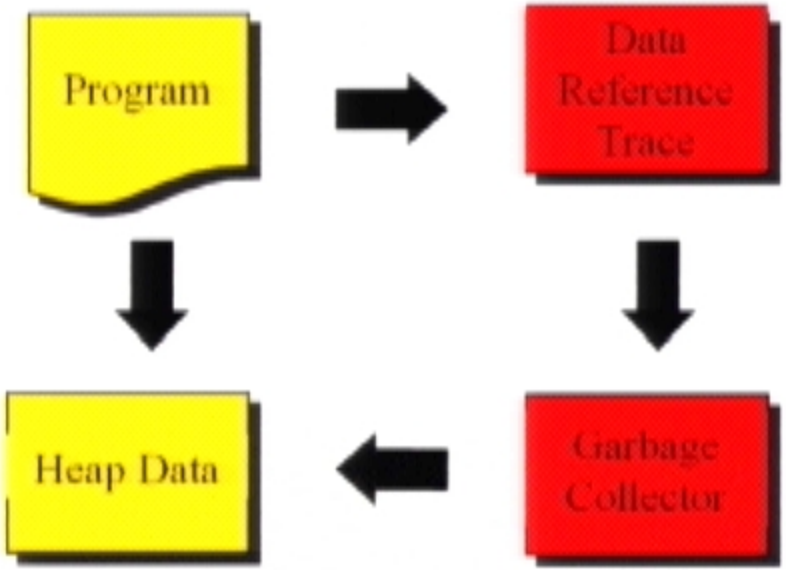

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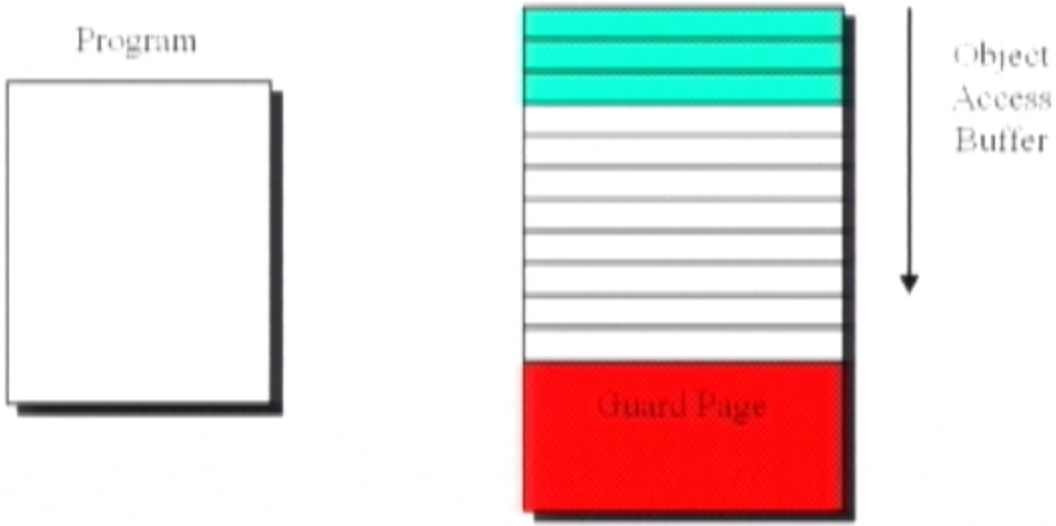

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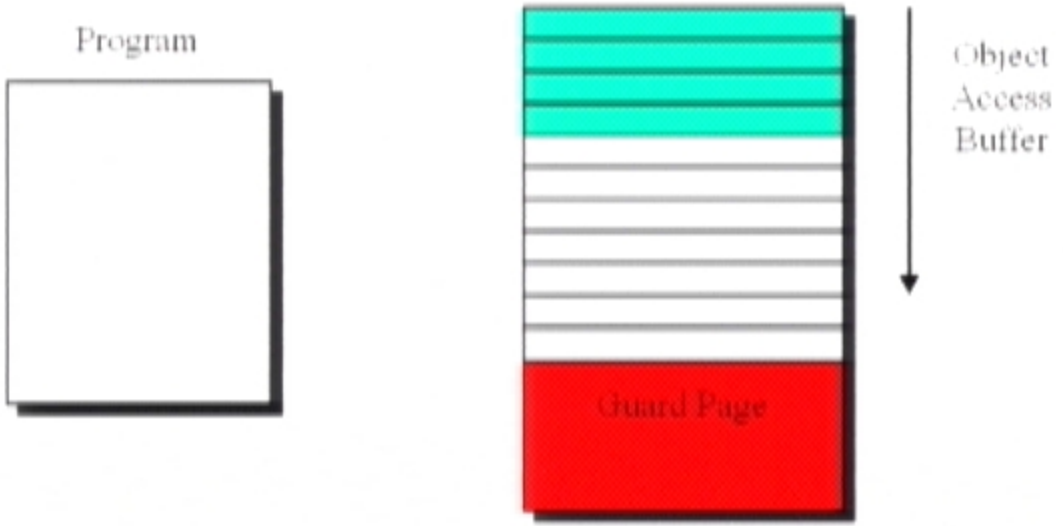

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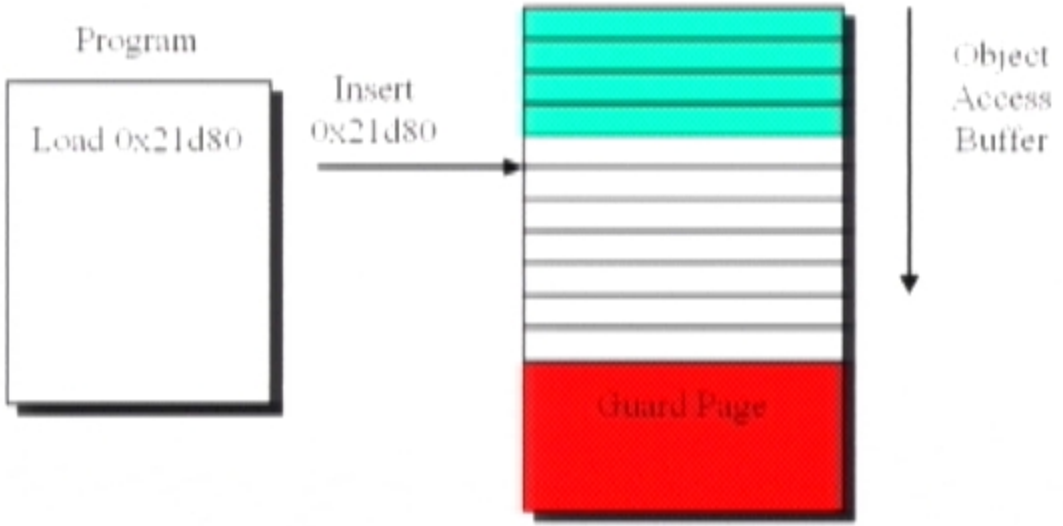

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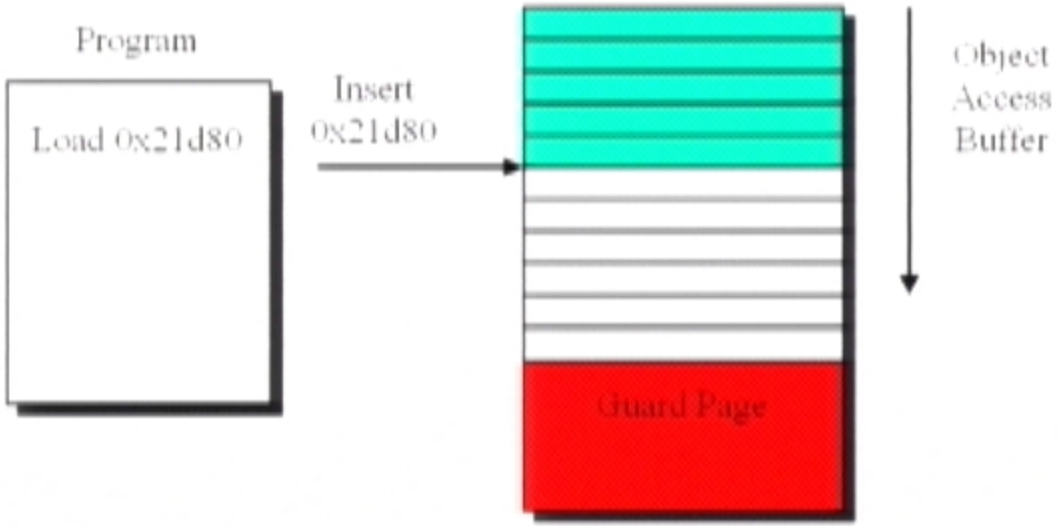
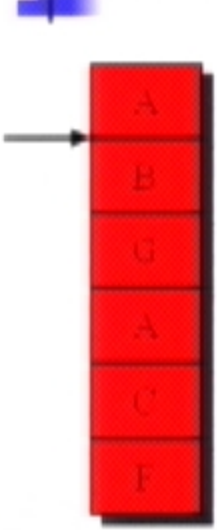


# Constructing the Object Affinity Graph


Object Access Buffer

Locality Queue

# Constructing the Object Affinity Graph



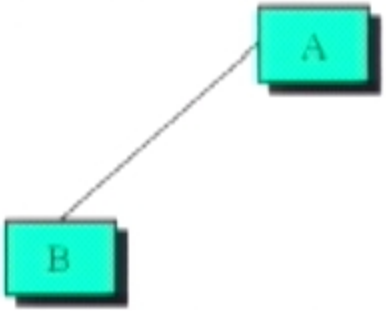


Object Affinity Graph

Object Access Buffer

Locality Queue

# Constructing the Object Affinity Graph

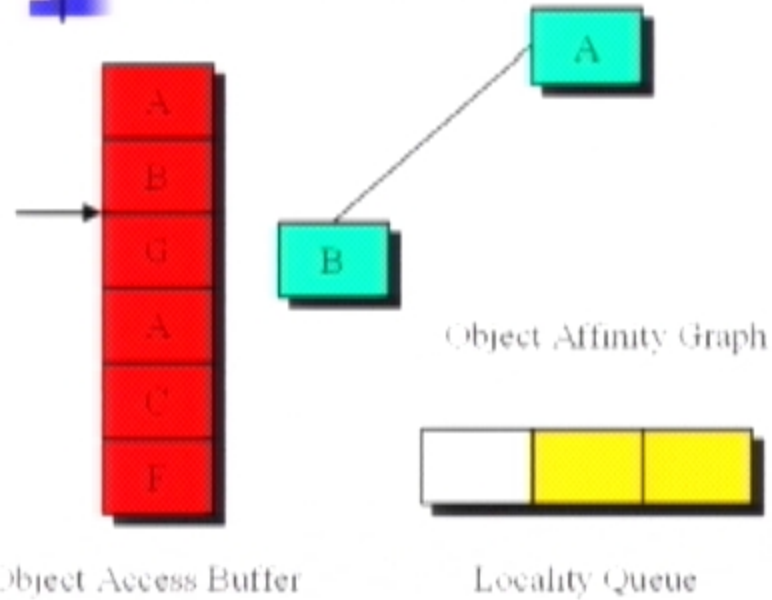




Object Affinity Graph

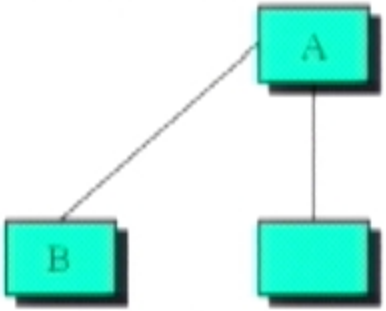
Locality Queue

Object Access Buffer

# Constructing the Object Affinity Graph



# Constructing the Object Affinity Graph

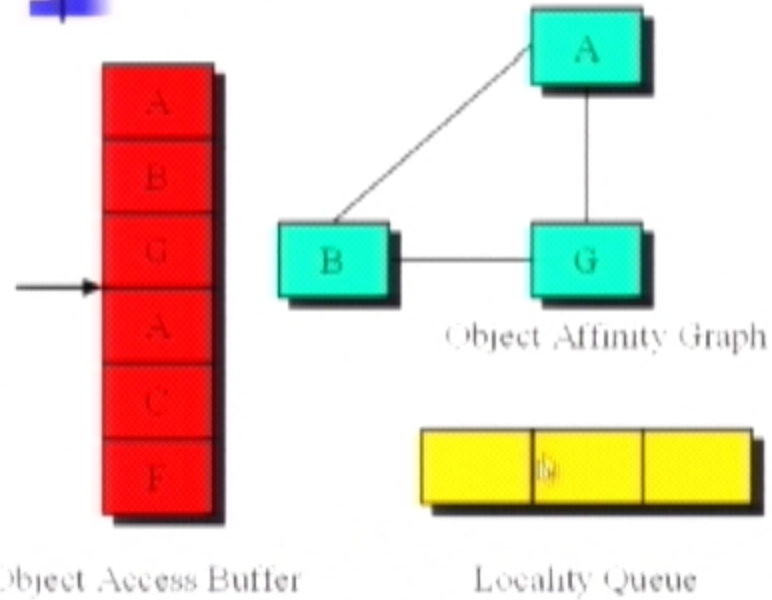




Object Affinity Graph

Object Access Buffer

Locality Queue

# Constructing the Object Affinity Graph



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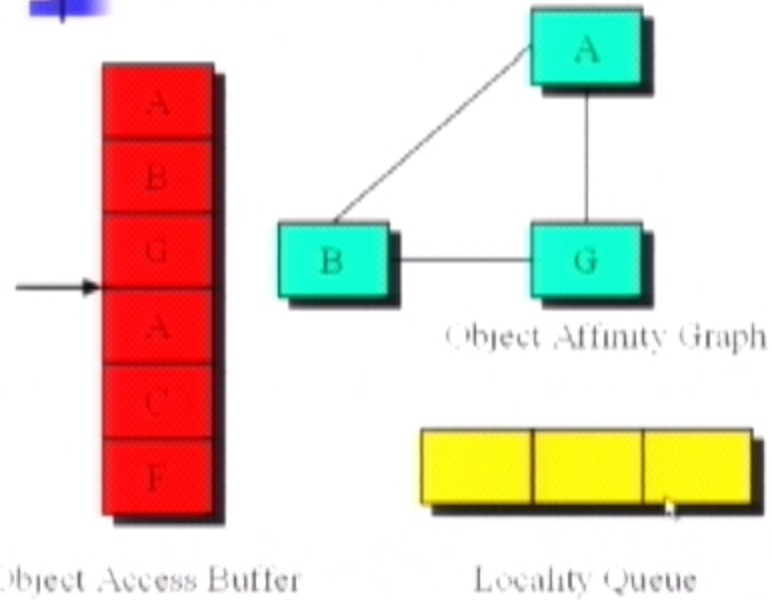

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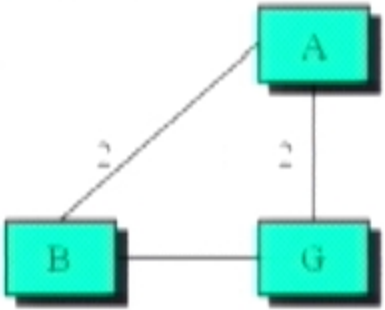
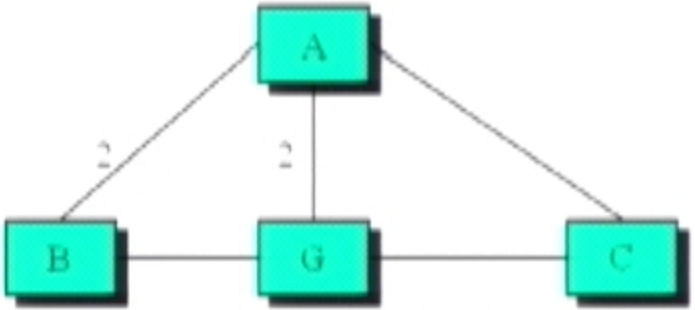



Object Affinity Graph

Object Access Buffer

Locality Queue

# Constructing the Object Affinity Graph

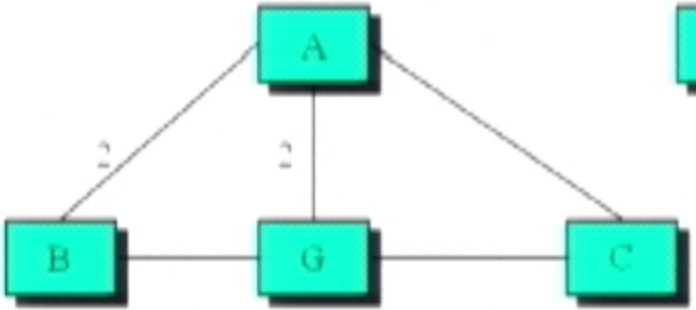




Object Affinity Graph

Object Access Buffer

Locality Queue

# Constructing the Object Affinity Graph

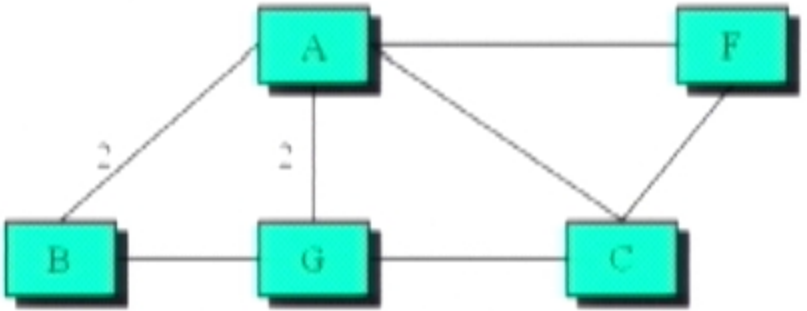

Object Affinity Graph

Object Access Buffer

Locality Queue

# Constructing the Object Affinity Graph


Object Access Buffer




Object Affinity Graph


Locality Queue

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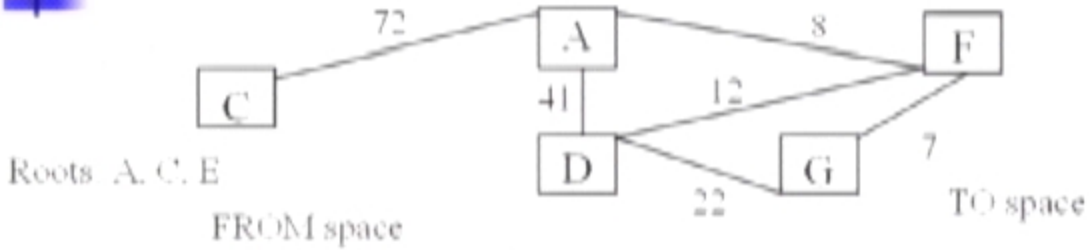


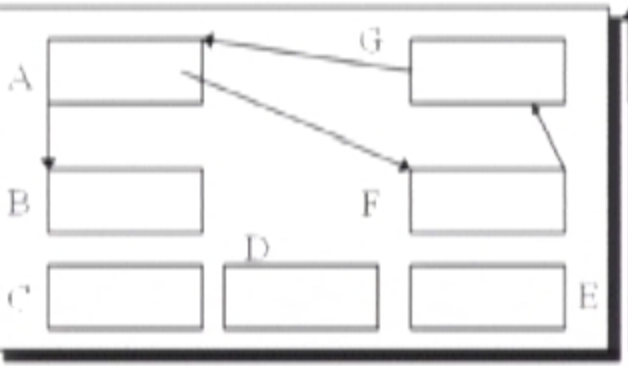

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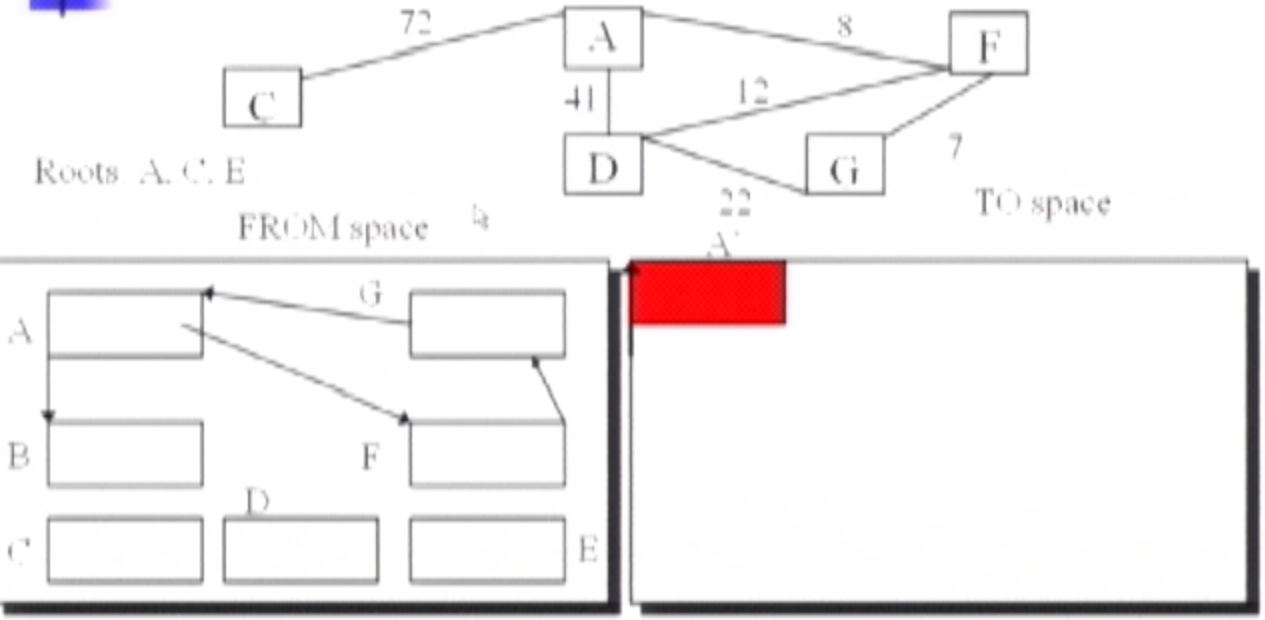

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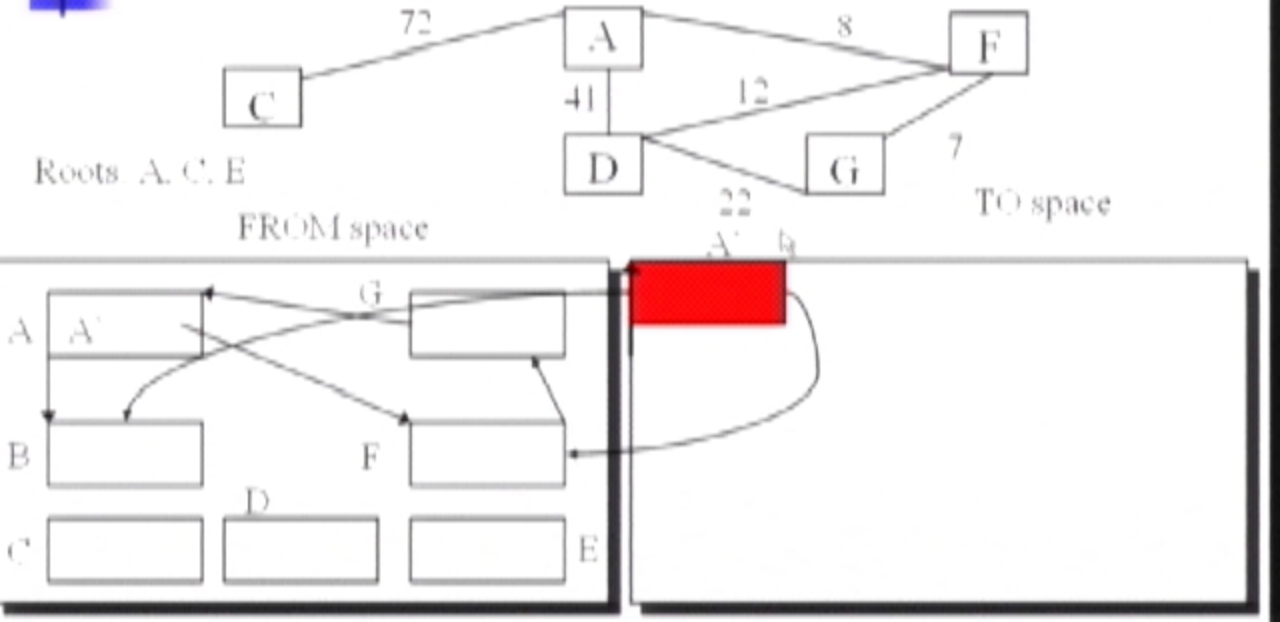

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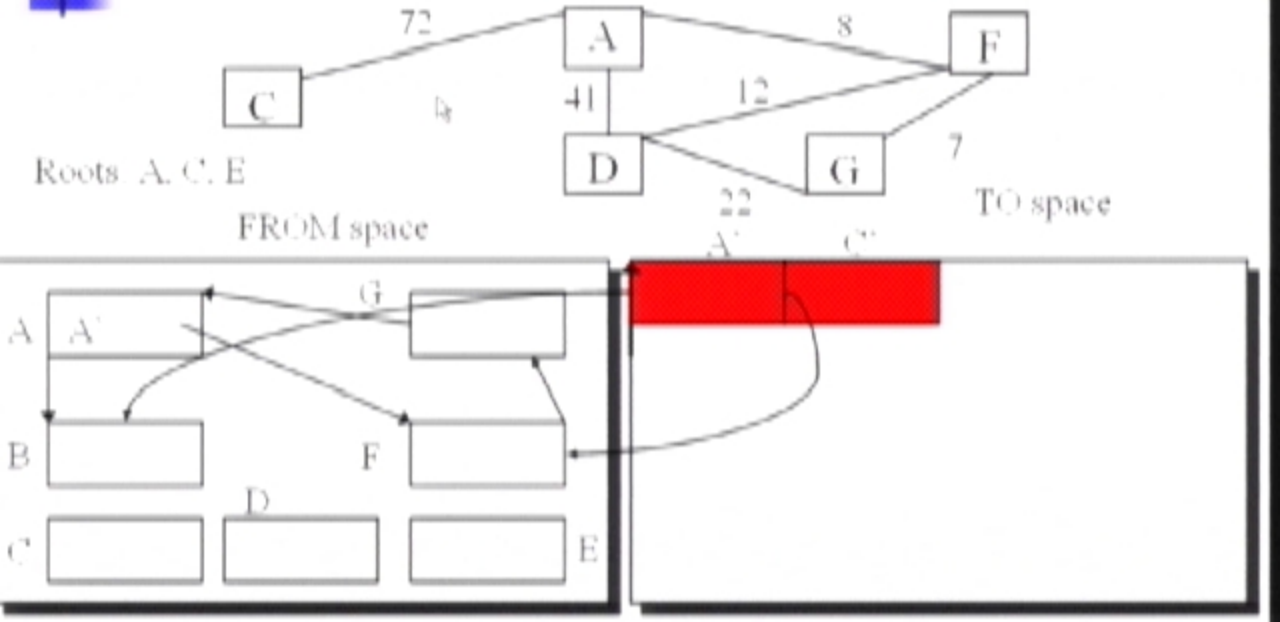

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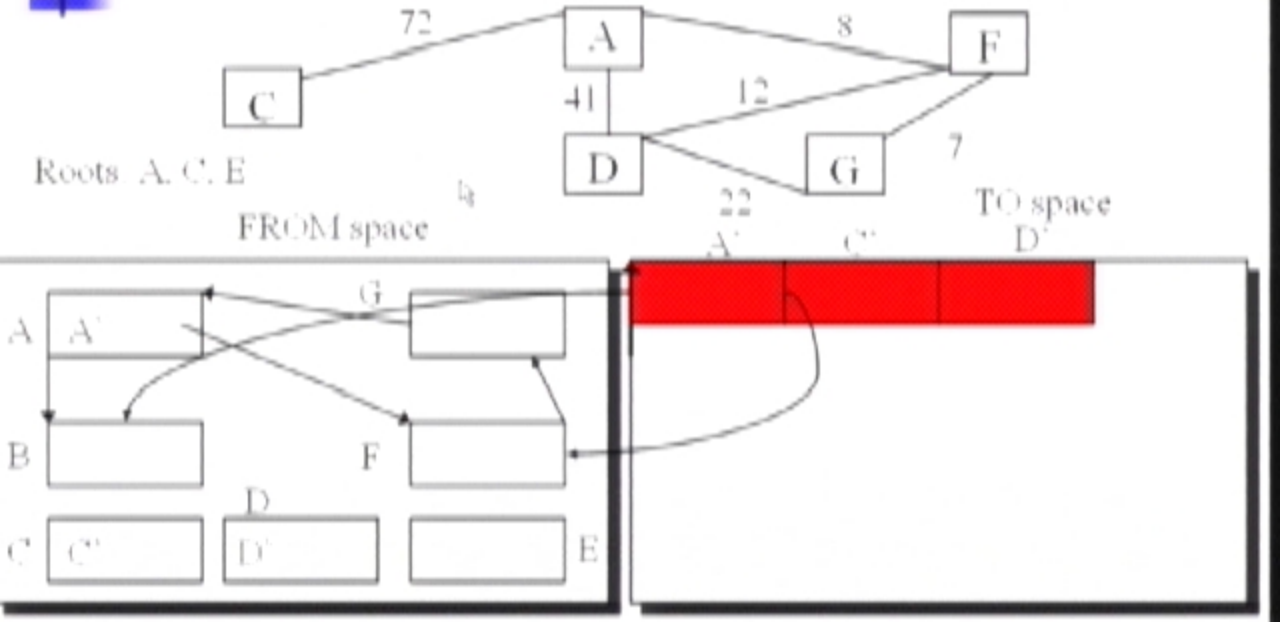

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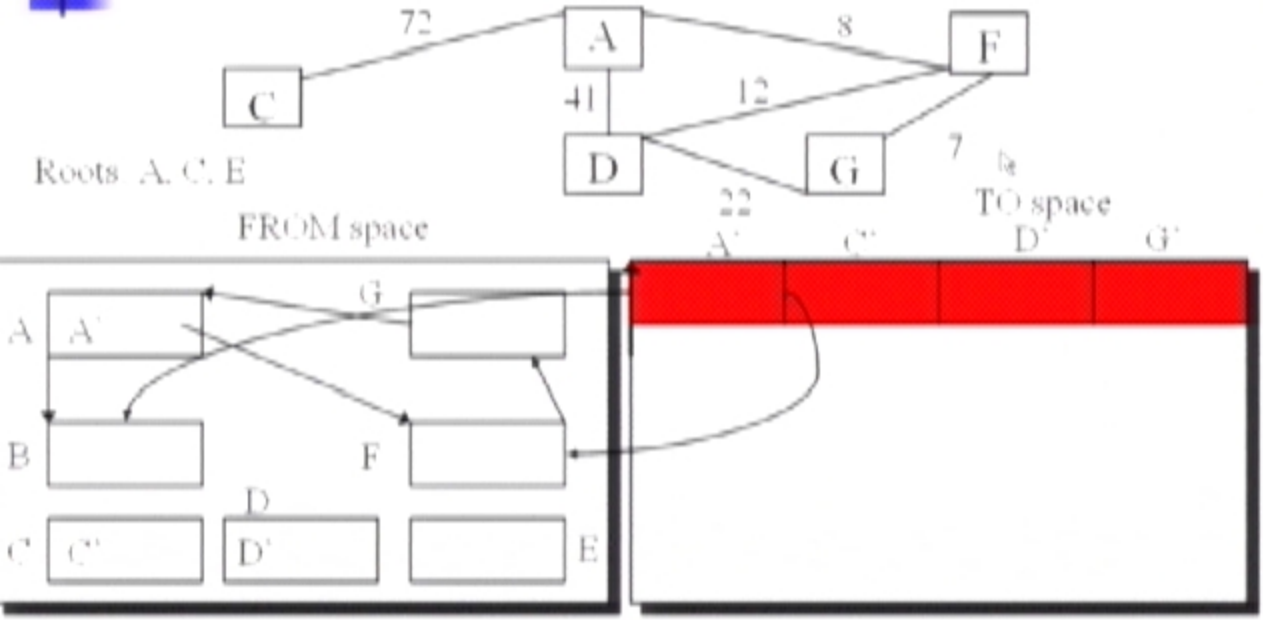

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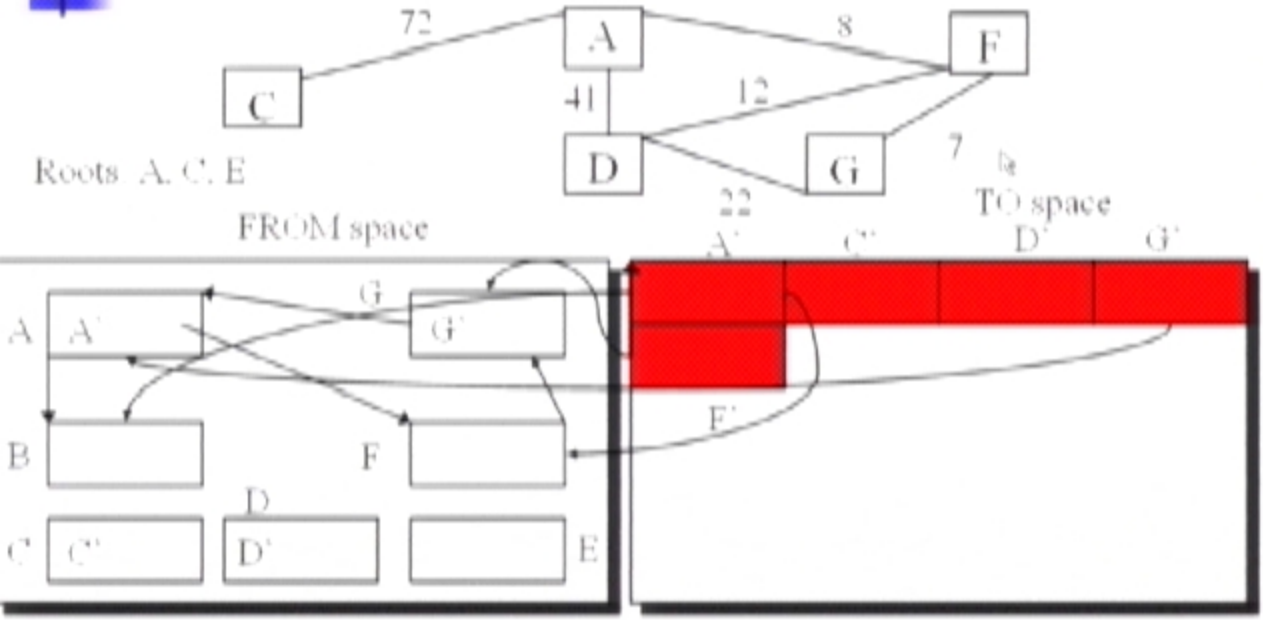

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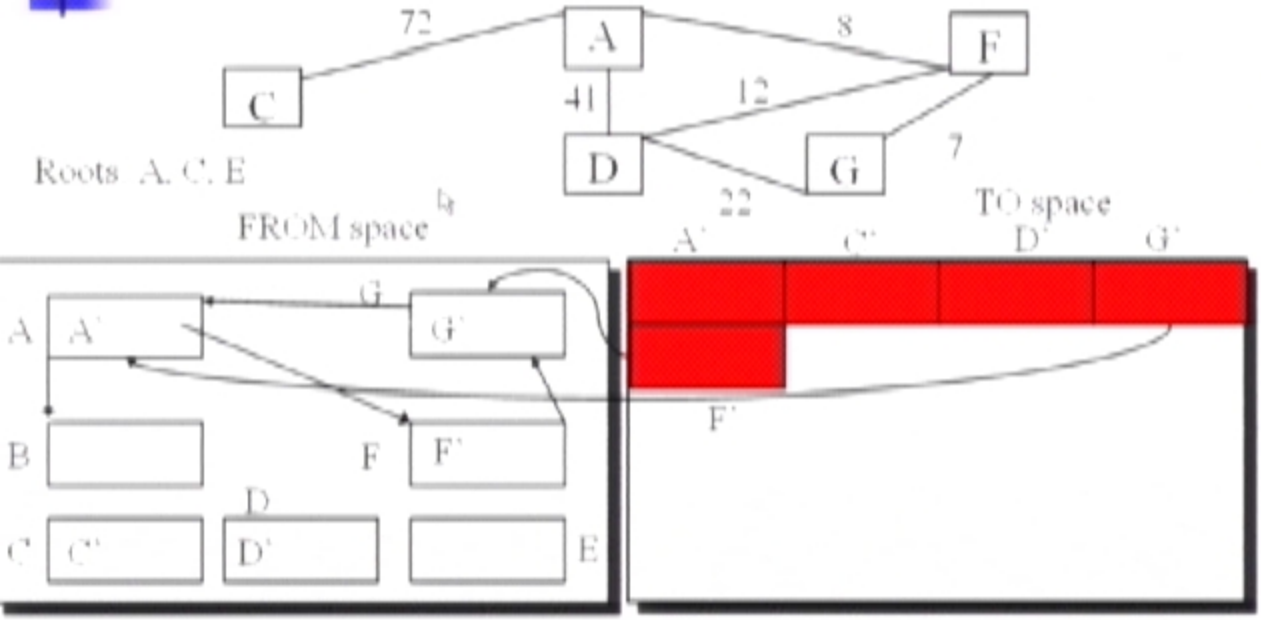

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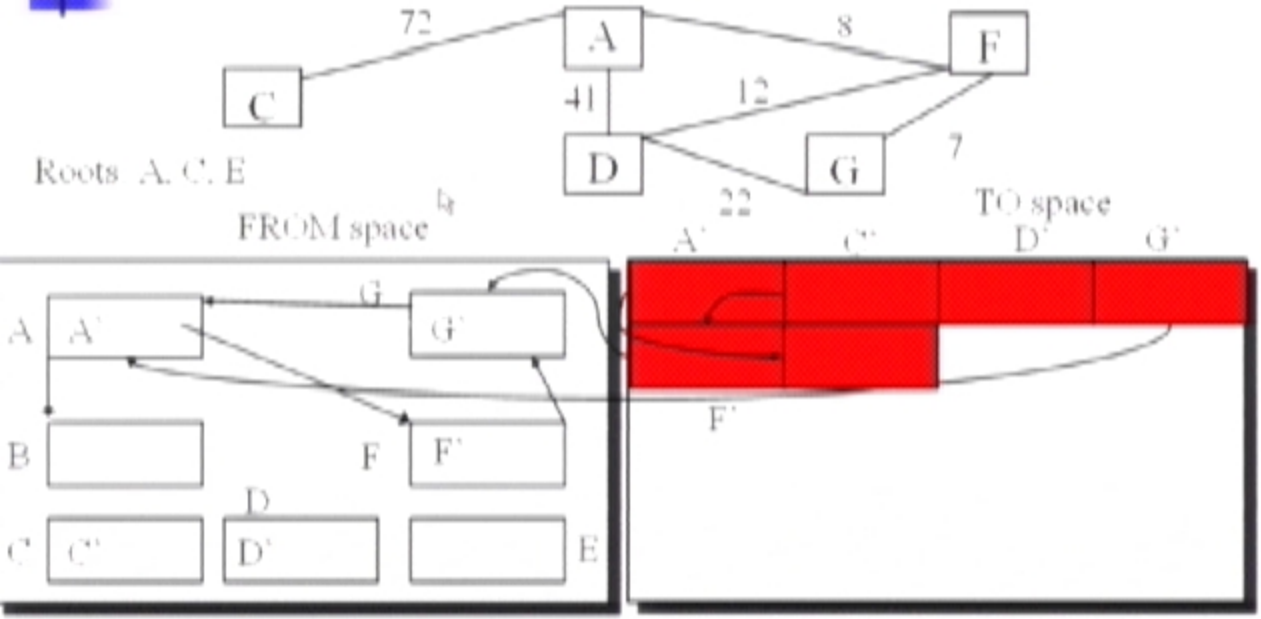

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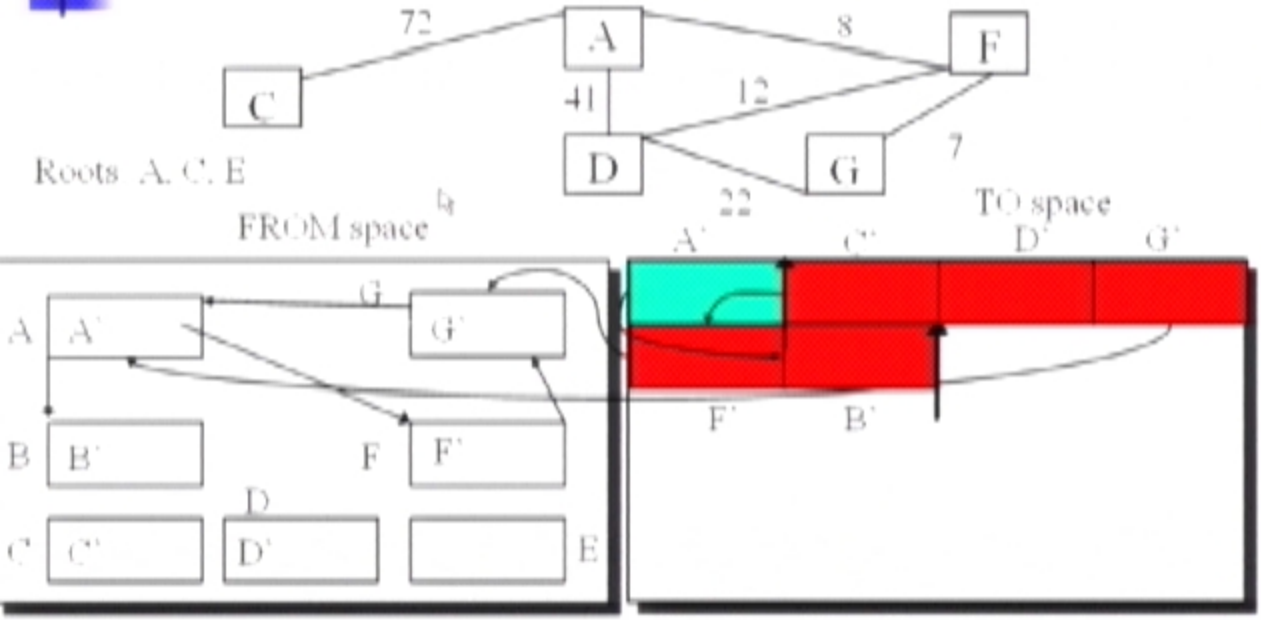

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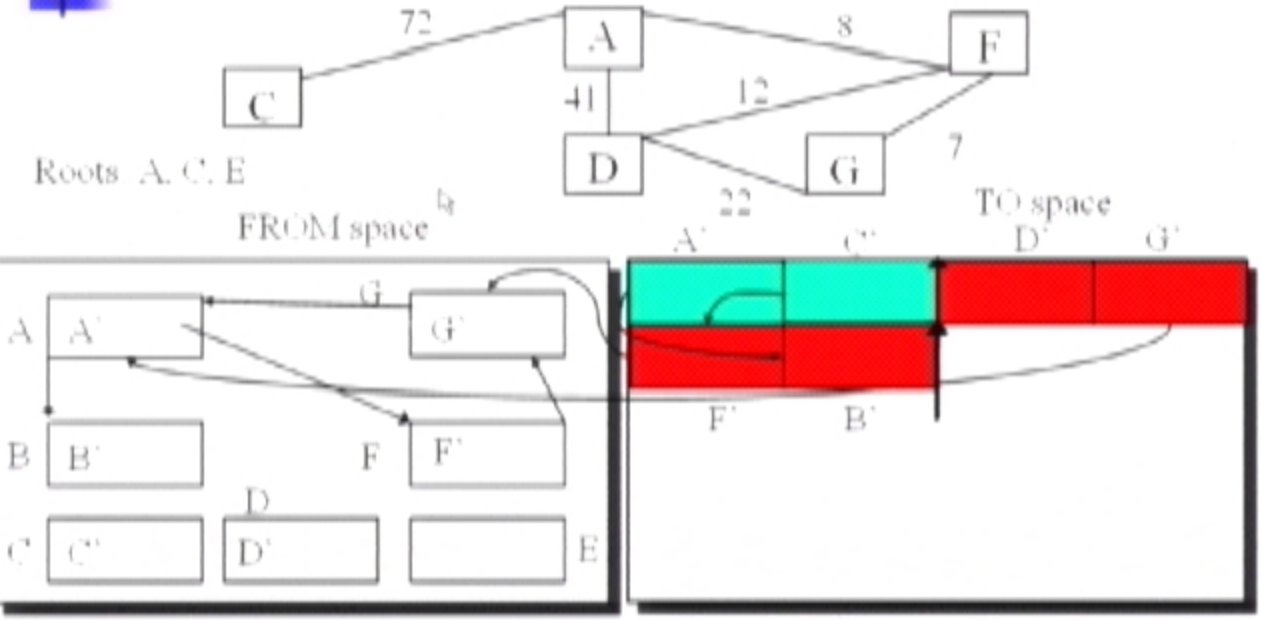

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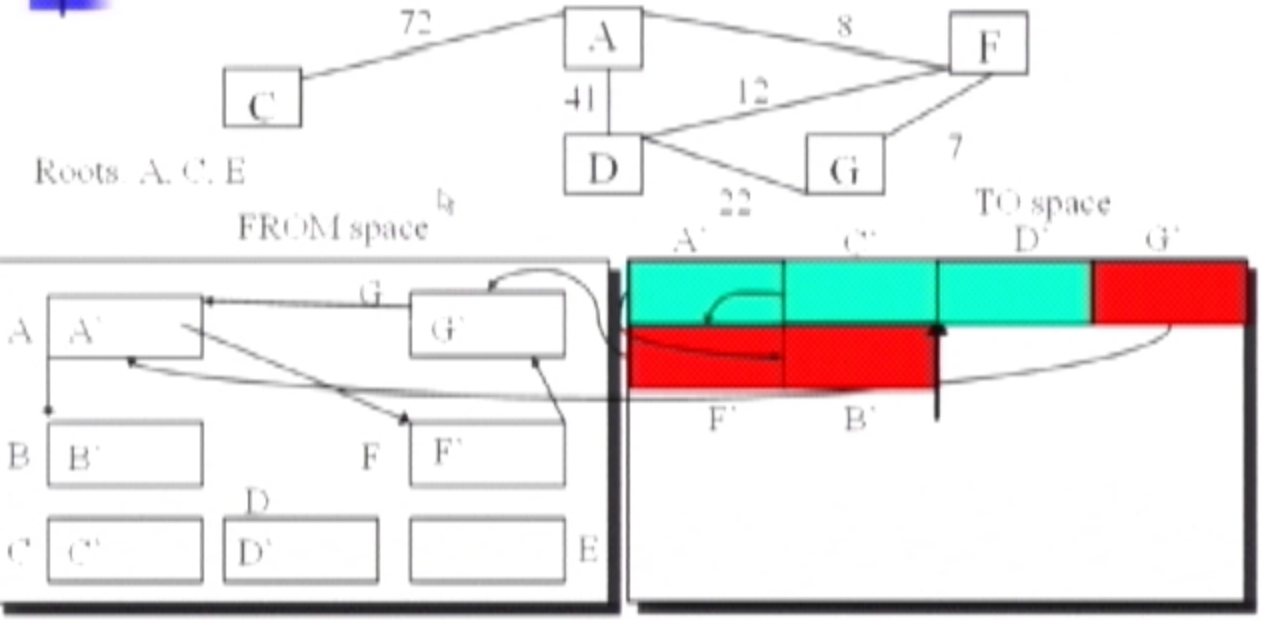

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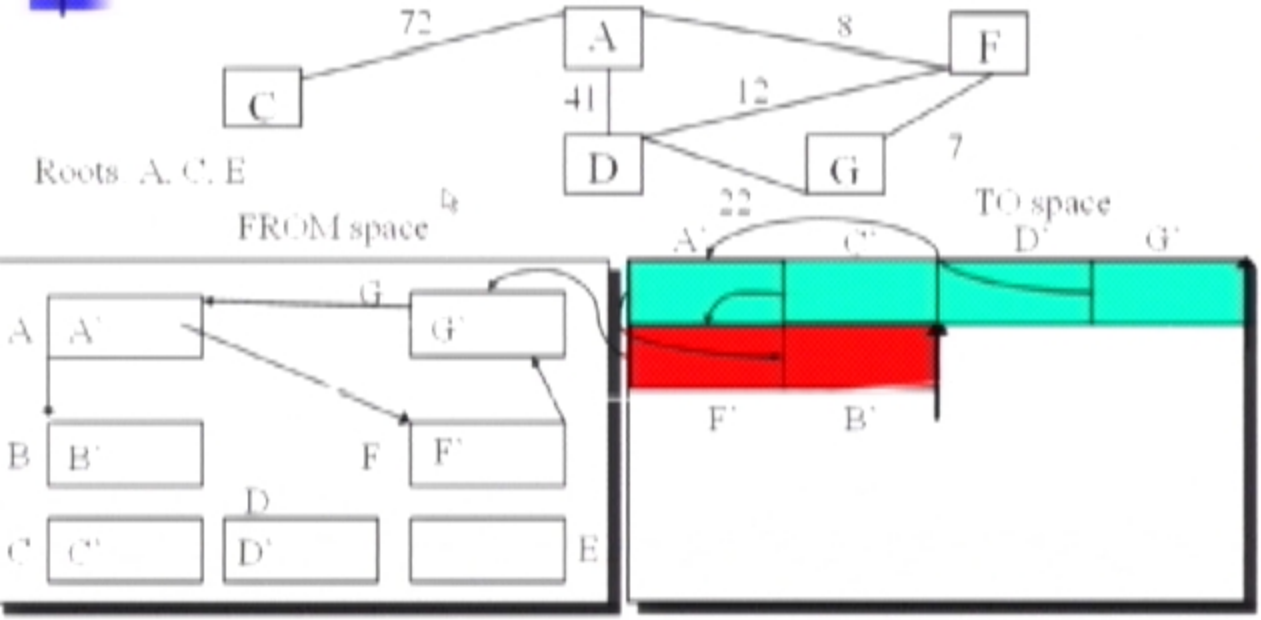

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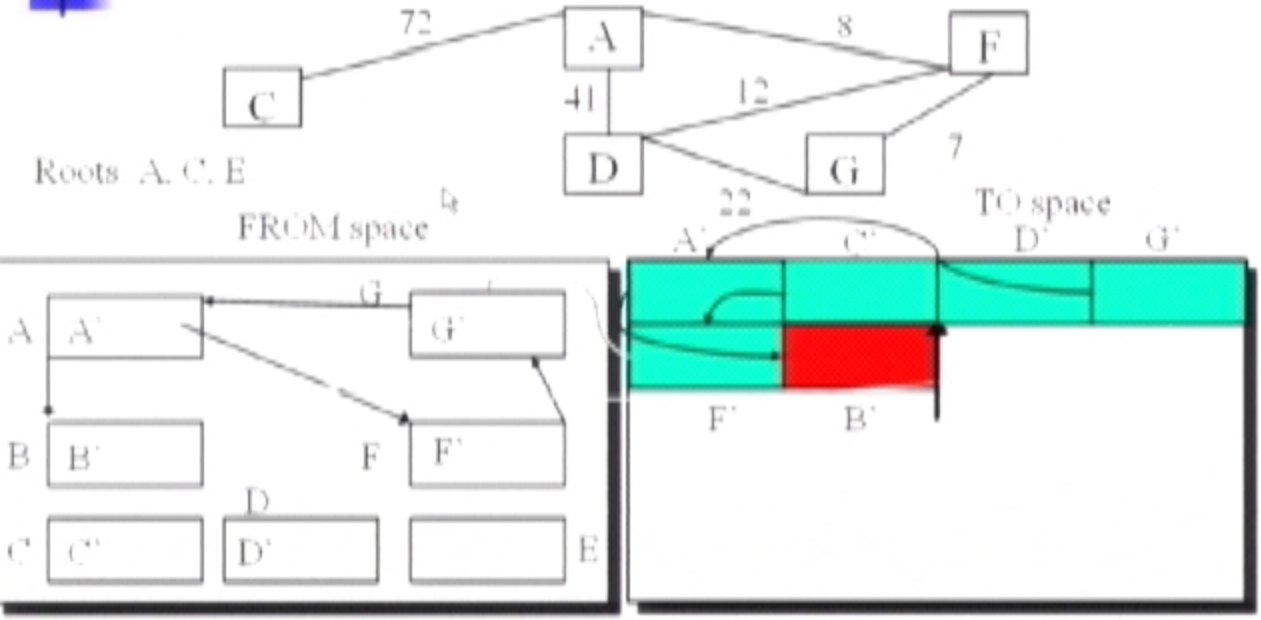

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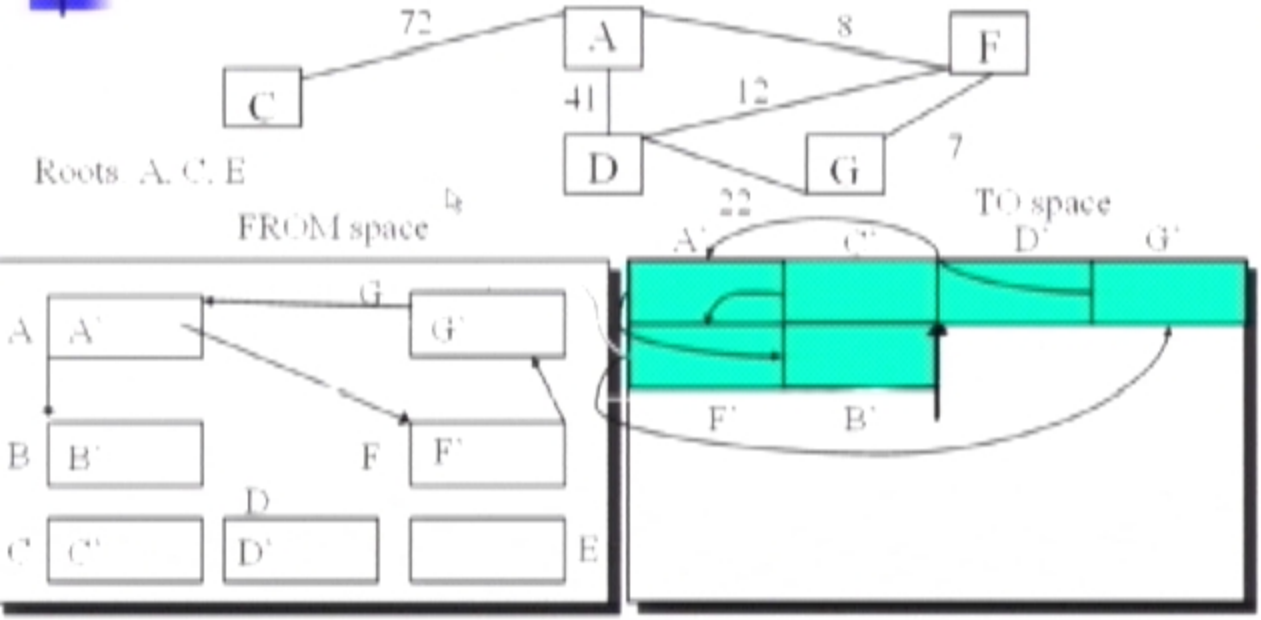

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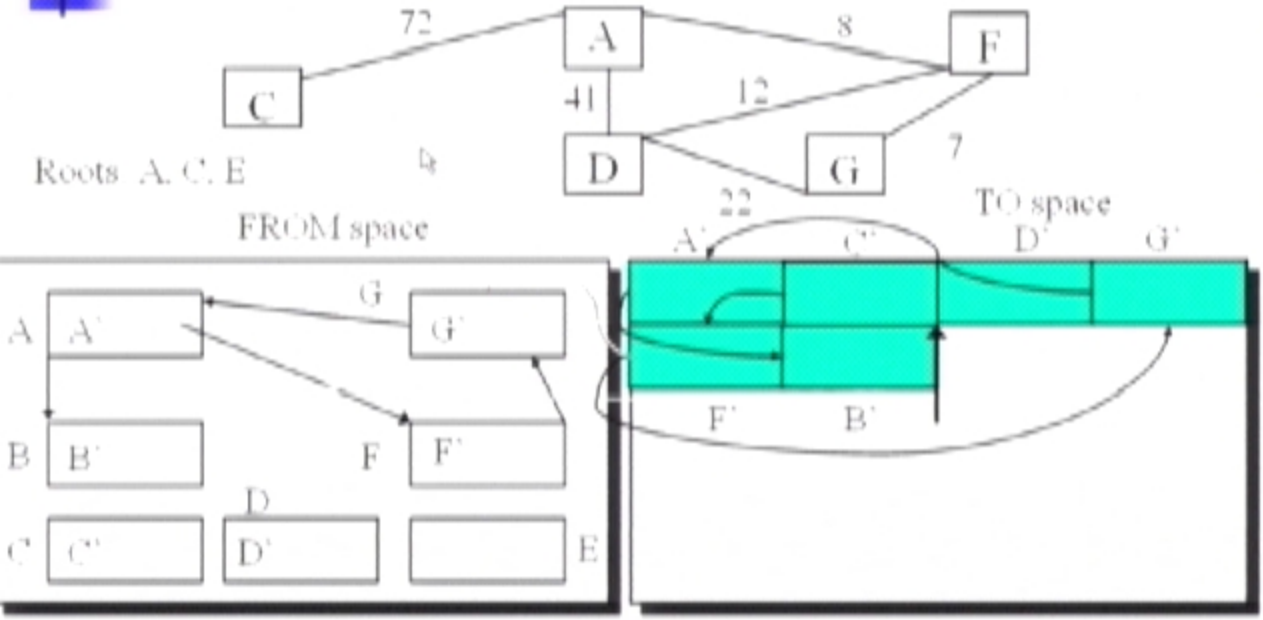

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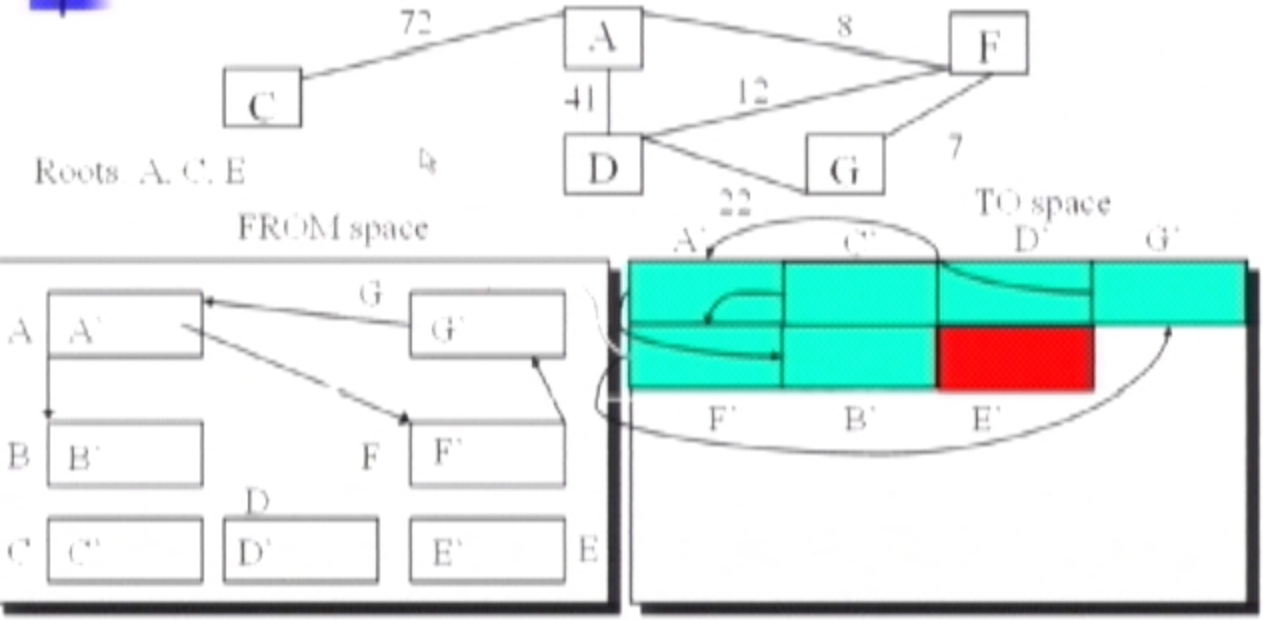

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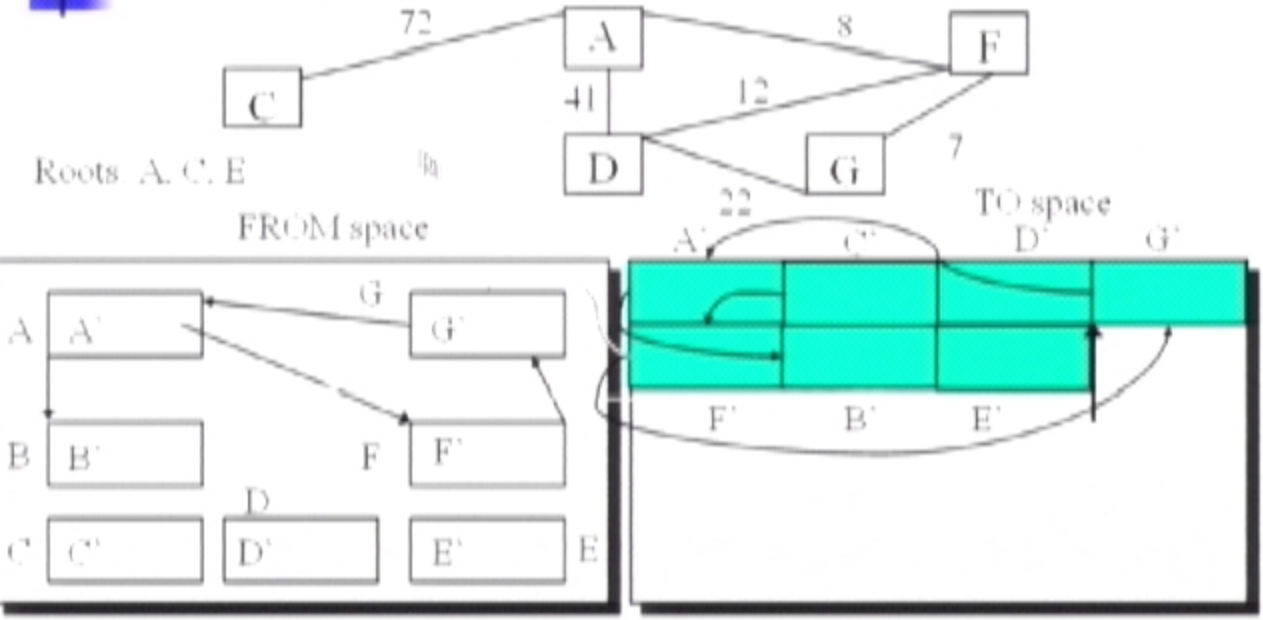
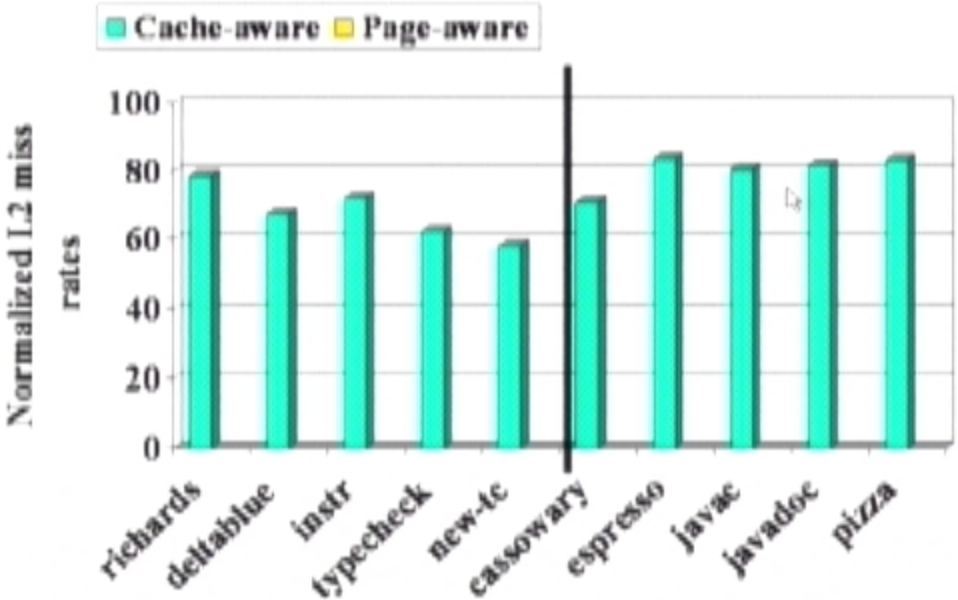


# Cache-Conscious Reorganization

# Cache-Conscious Reorganization



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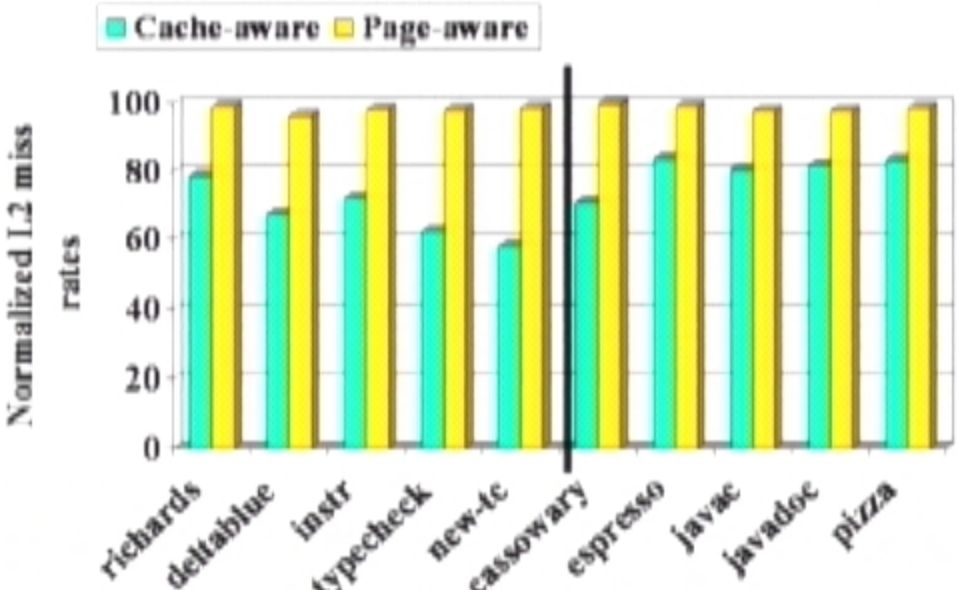

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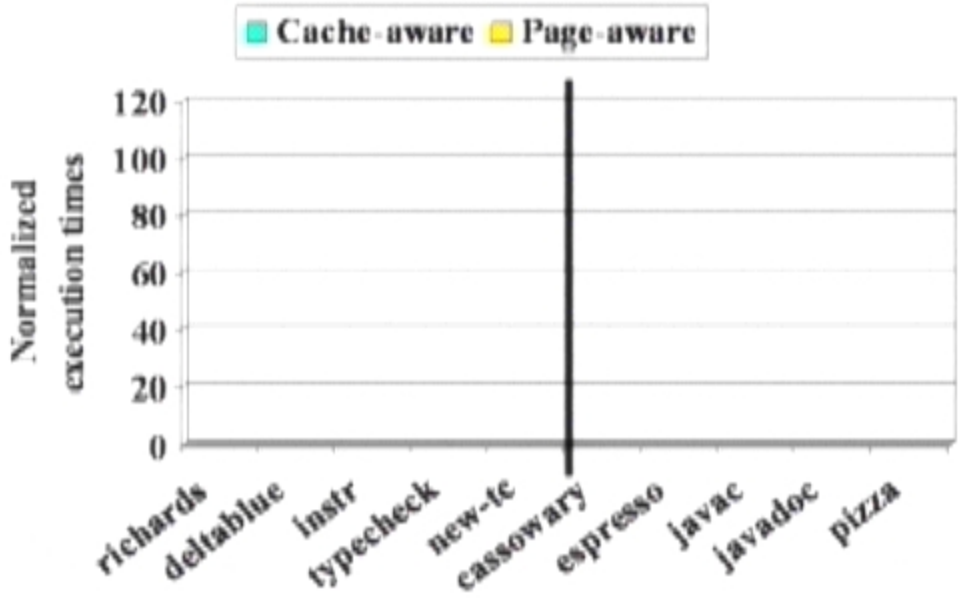

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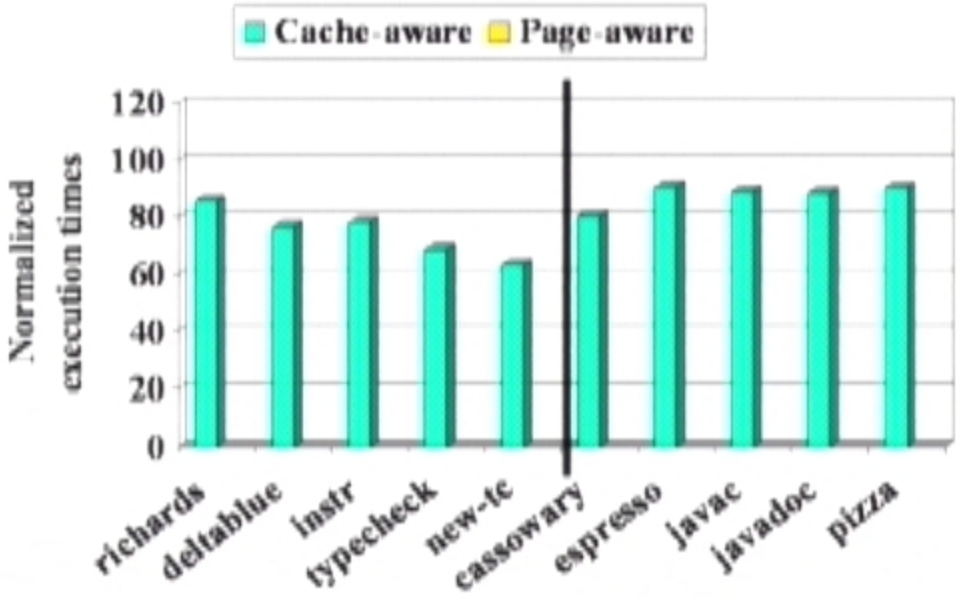

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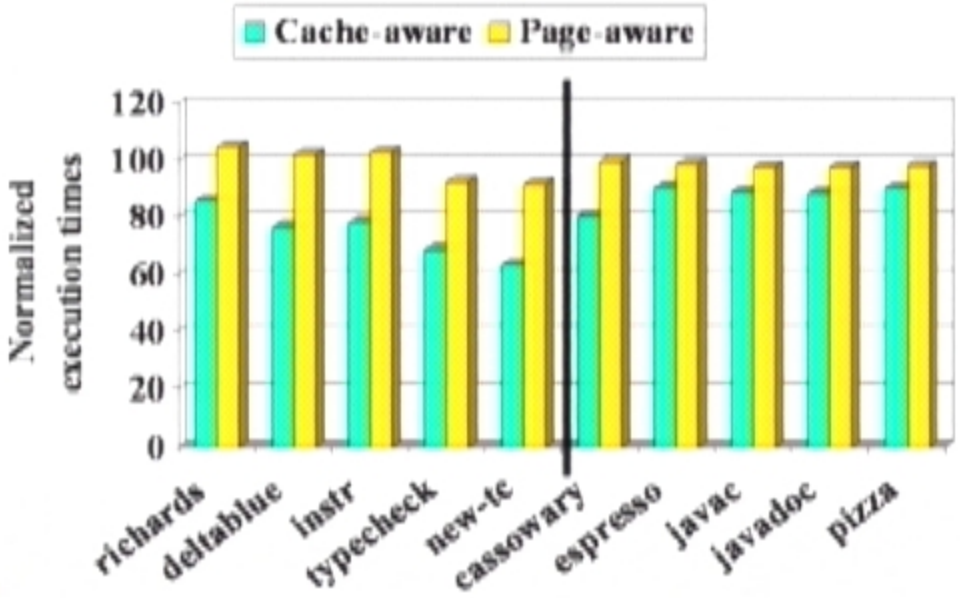
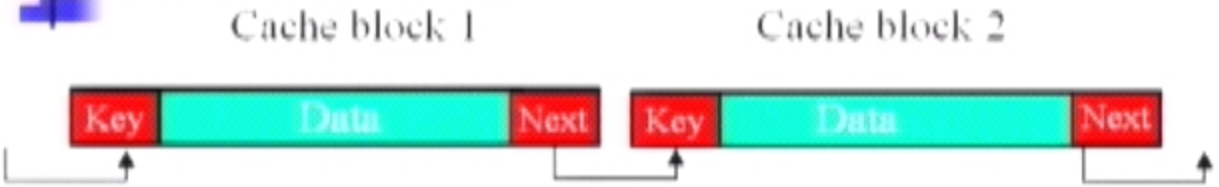
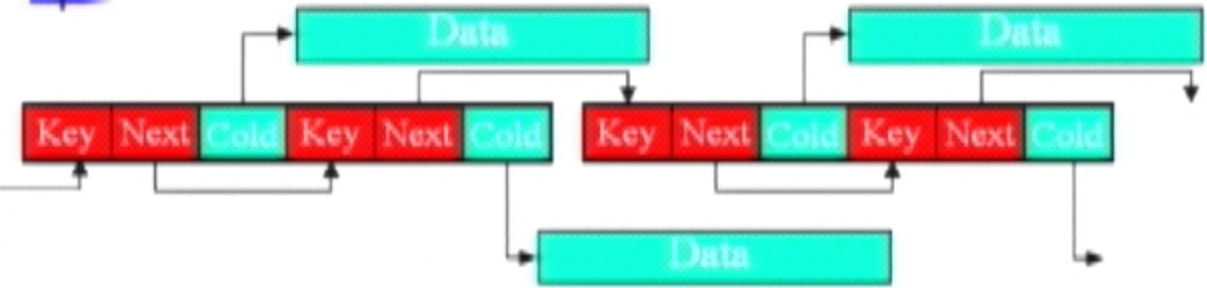


# Hot/Cold Structure Splitting




```
for(p = head; p != NULL; p = p->next){
      if(p->key == key){
            /* Examine p->data */
      }
}
```

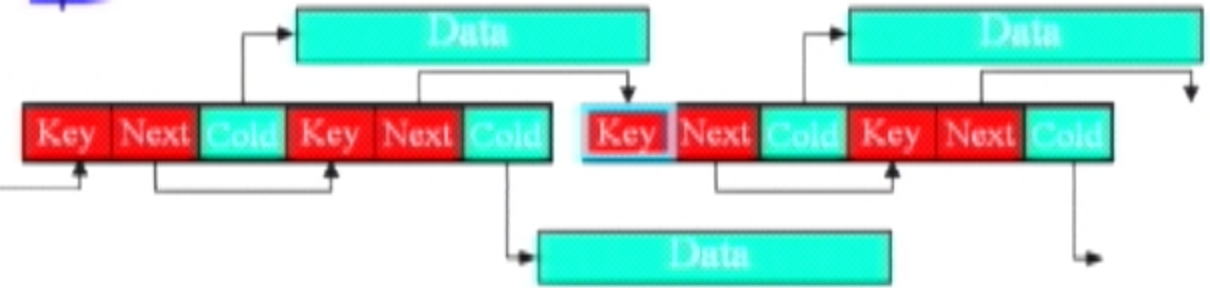
# Hot/Cold Structure Splitting




```
struct list {
 int key;
 struct list *next;
 struct cold_list *cold;
};
```

```
struct cold_list {
 int data[100];
};
```

# Hot/Cold Structure Splitting




```
struct list {
 int key;
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};
```

```
struct cold_list {
 int data[100];
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```
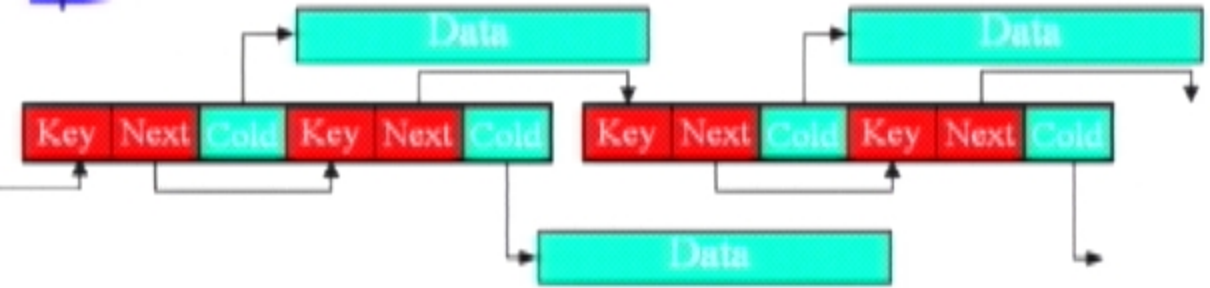

# Hot/Cold Structure Splitting



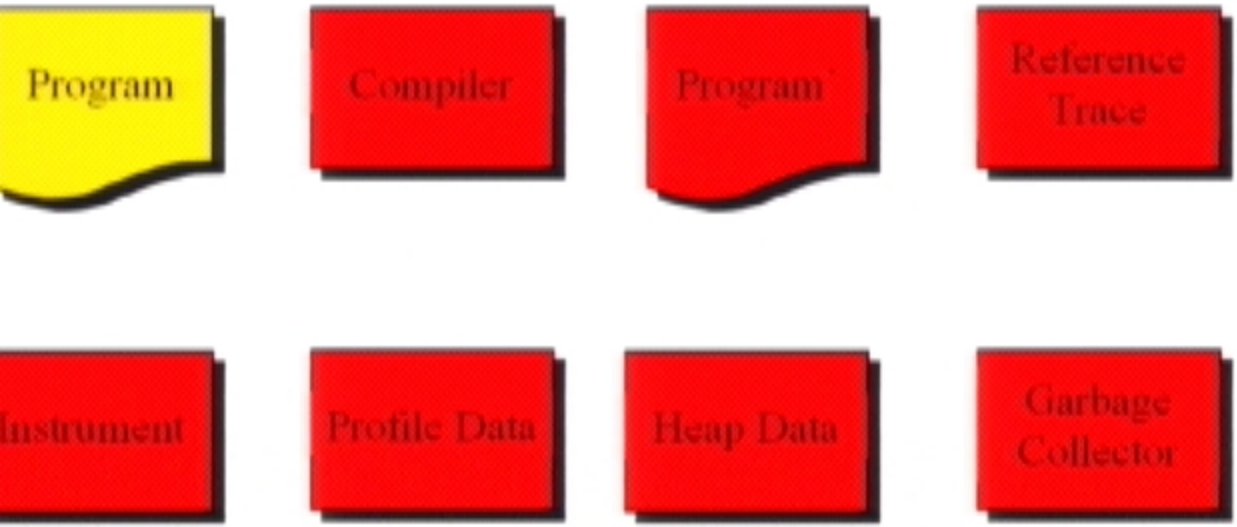

```
struct list {
 int key;
 struct list *next;
 struct cold_list *cold;
};
```

```
struct cold_list {
 int data[100];
};
```

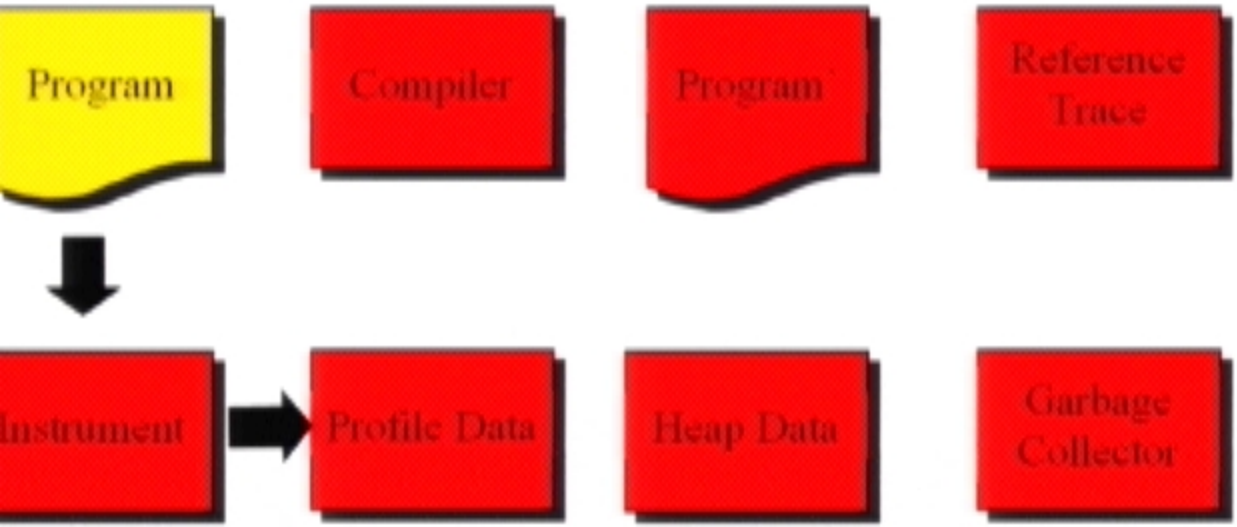
# Hot/Cold Structure Splitting Algorithm

- Profile field access counts
- Identify hot structure fields
- Remove cold fields & place in new structure (link from old)
- Insert additional allocation call for new structure
- Access cold fields through new structure

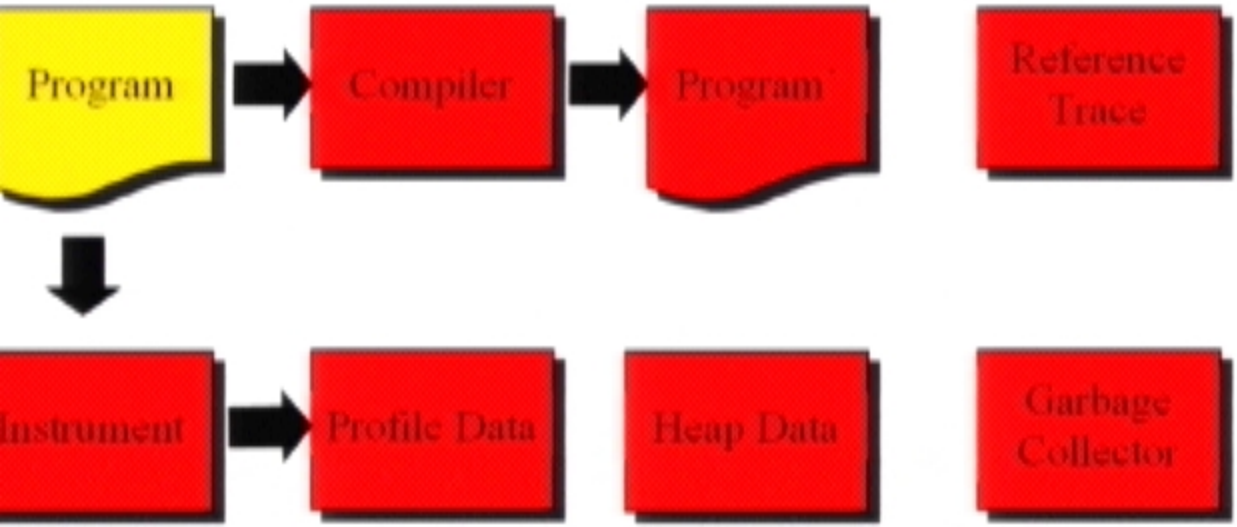
# Cache-Conscious Reorganization (with Structure Splitting)



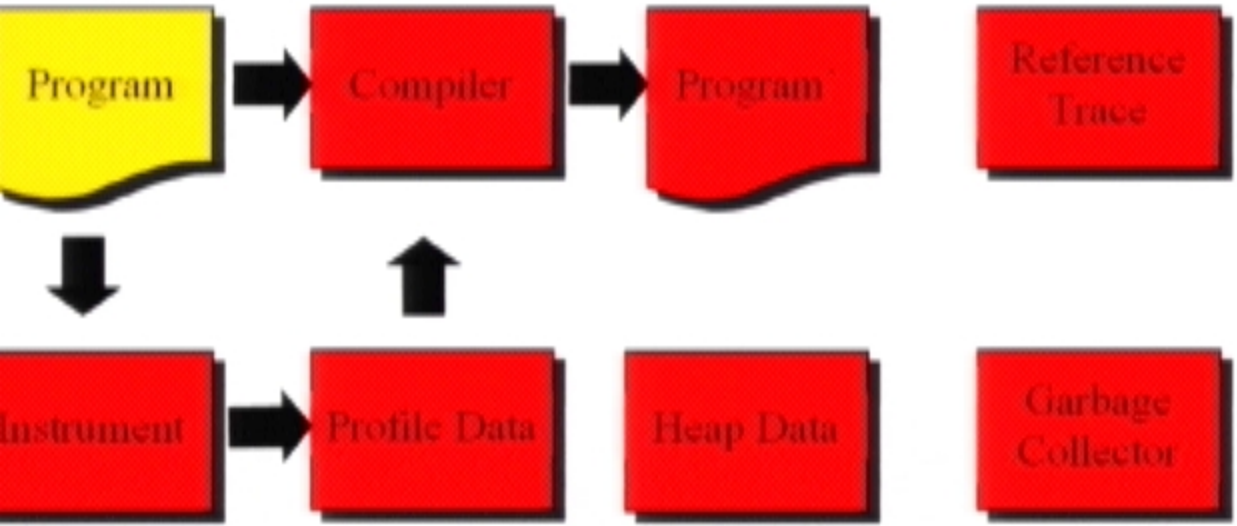
# Cache-Conscious Reorganization (with Structure Splitting)



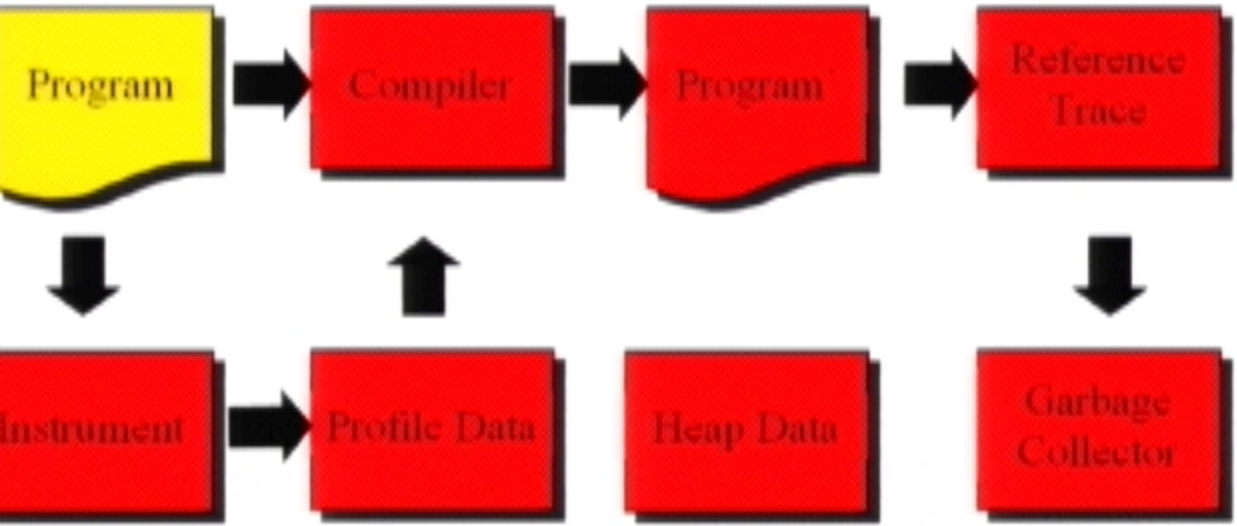
# Cache-Conscious Reorganization (with Structure Splitting)



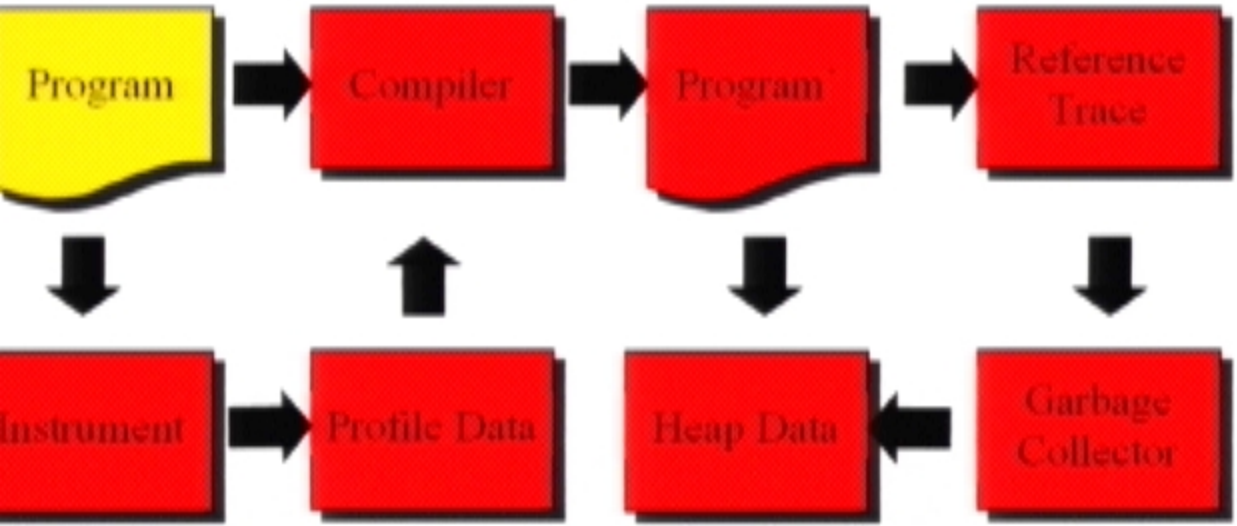
# Cache-Conscious Reorganization (with Structure Splitting)



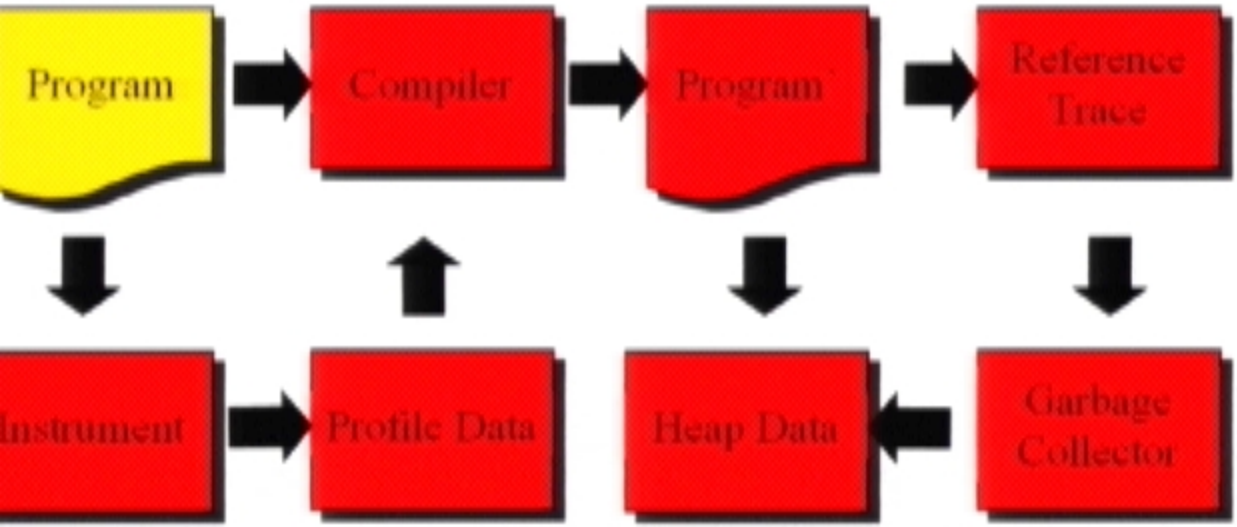
# Cache-Conscious Reorganization (with Structure Splitting)



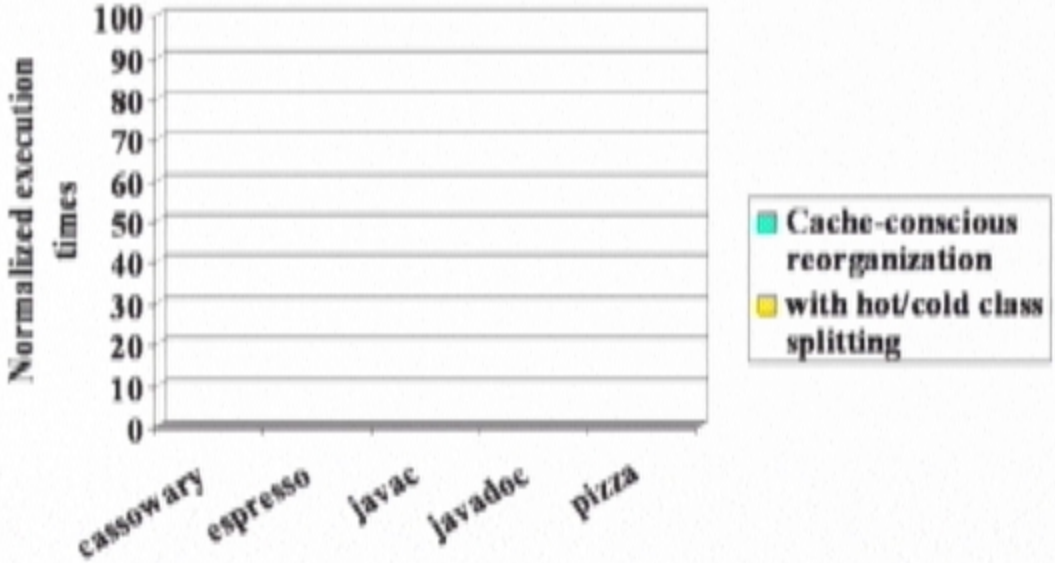
# Cache-Conscious Reorganization (with Structure Splitting)



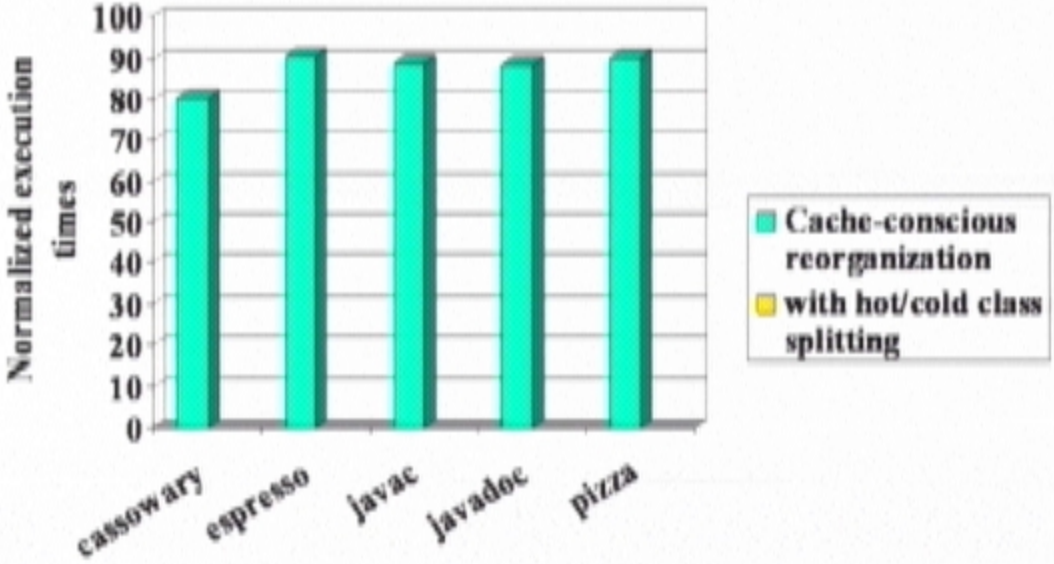
# Cache-Conscious Reorganization (with Structure Splitting)



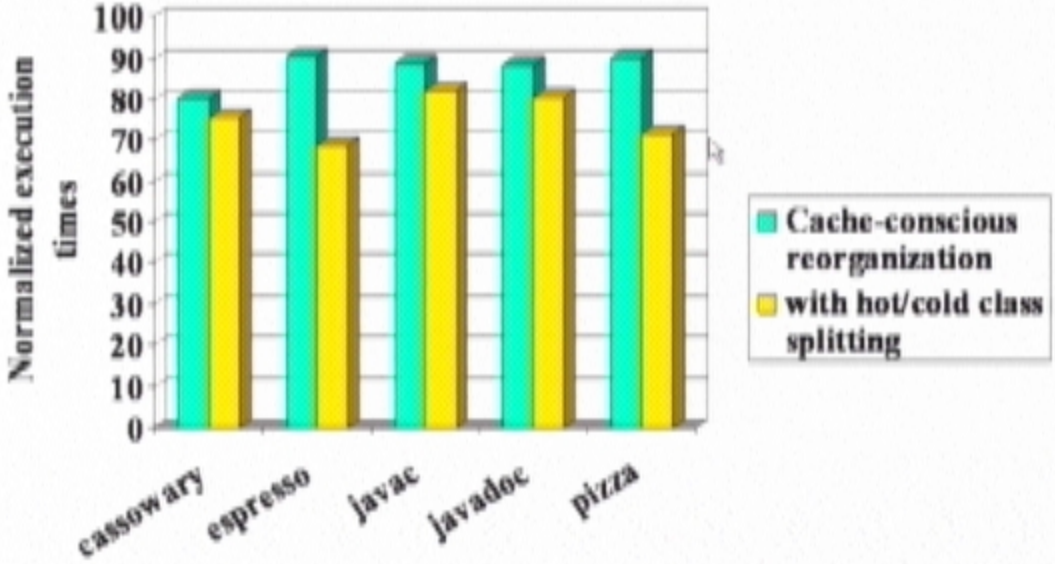
# Hot/Cold Class Splitting



# Hot/Cold Class Splitting



# Hot/Cold Class Splitting



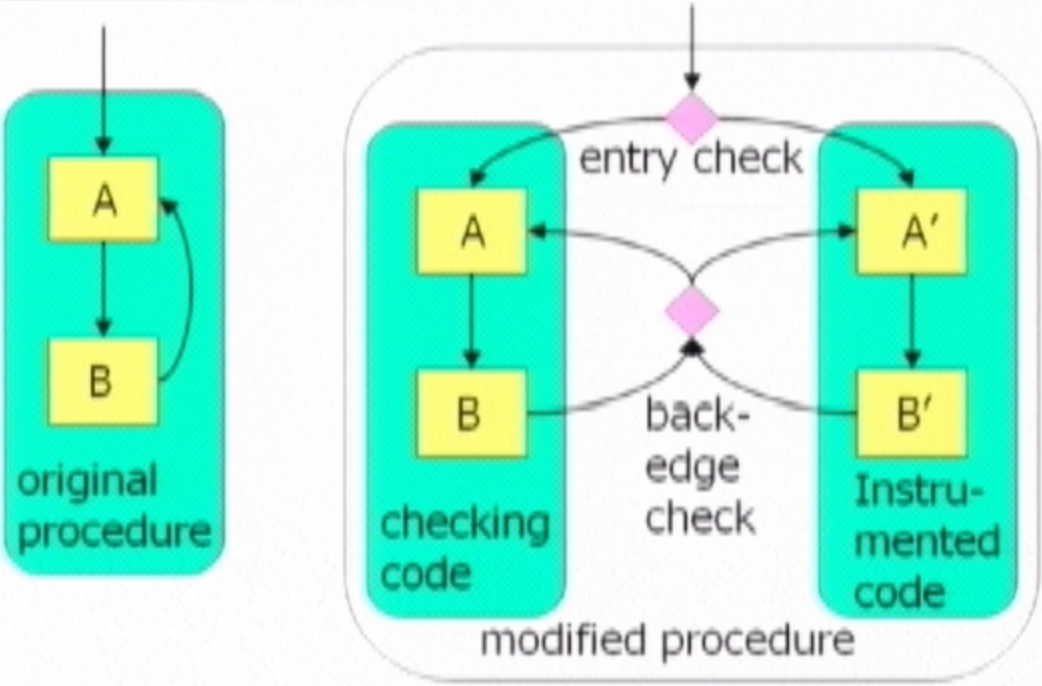
# Limitations

- Low-overhead data reference profiling
  - Requires reserving register
  - Potentially inaccurate compiler analysis
- Object Affinity Graph
  - Approximates temporal relationships
  - Higher accuracy increases processing cost

# Talk Outline

- Background and Motivation
- GC for implementing cache-conscious data layouts
- Low-overhead data reference profiling
- Fast and accurate data layout determination

# Low-overhead data reference profiling



# Low-overhead data reference profiling

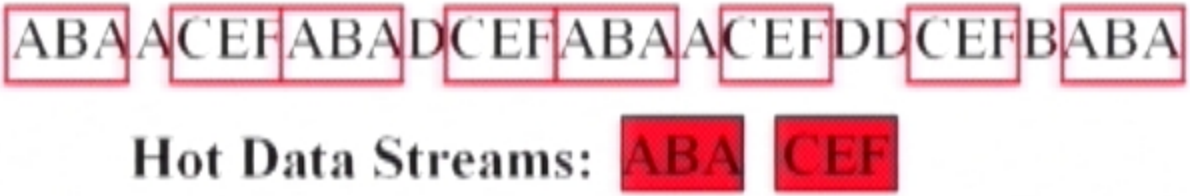
- 0.1% sampling rate provides high accuracy
- 5% overhead at this sample rate
- Base case is highly optimized x86 code

# Talk Outline

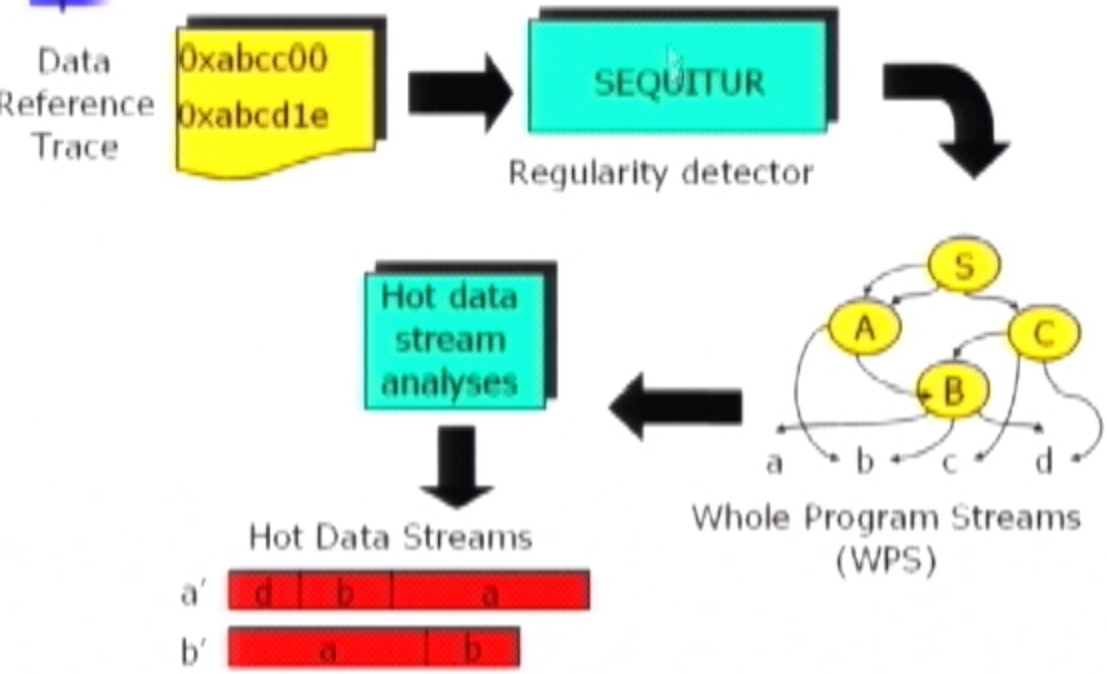
- Background and Motivation
- GC for implementing cache-conscious data layouts
- Low-overhead data reference profiling
- Fast and accurate data layout determination

# Exploitable Locality

- Hot Data Streams:
  Data object sequences that frequently repeat
- Hot=>reference skew + Repetition=>regularity
- Analogous to hot program paths



# Computing Exploitable Locality



# Fast, accurate data layout determination

- Fast linear time algorithms
  - Construct Whole Program Stream representation
  - Detect hot data streams
- Few seconds, yet precise information

# Conclusions

- Cache-conscious layouts offer large benefits
- GC for cache-conscious data layouts
  - Structure layout reorganization
  - Hot/cold splitting
- Practical within context of CLR
  - Low-overhead data reference profiling
  - Fast, accurate data layout determination
- Opportunity for C# to approach performance of C/C++

# Future

- Implement and evaluate in the context of the CLR

# References (http://research.microsoft.com/~trishulc)

- GC for cache-conscious data layout
  - Using GC to implement cache-conscious data layout, ISMM 98
  - Cache-conscious structure definition, PLDI 1999
- Low-overhead data reference profiling
  - Bursty tracing: A low-overhead framework for temporal profiling, FDDO 2001 submission
- Fast, accurate data layout determination
  - Efficient data reference locality abstractions and representations, PLDI 2001